A High Performance Ku-Band Two Channel Downconverter for Interferometric Radar Applications

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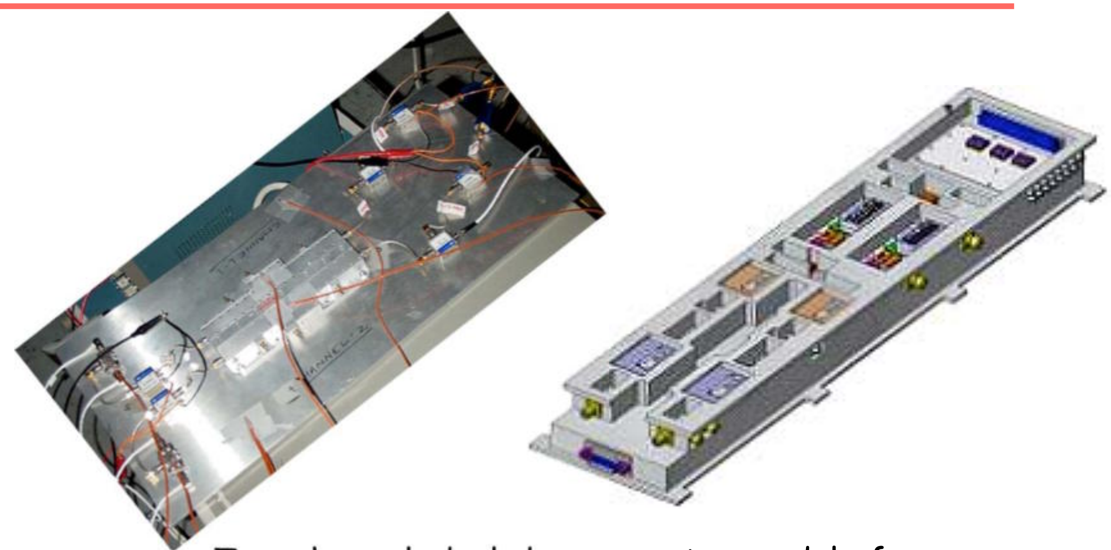
Advanced Performance Ku- and Ka-band Dual-Downconverter

Paul Siqueira: UMass; Michael Tope: JPL

Objective

- To develop and build advanced-performance Ku- and Ka-band Dual-DownConverters (DDCs) for use in spaceborne interferometric radar applications.
- Characterize performance of prototypes using recently developed measurement techniques that provide high accuracy.



Two-channel, dual-downcoverter module for Interferometric radar applications (breadboard and CAD model)

Approach

- Design, build, and test a Ku-band breadboard to guide construction of the Ku-band DDC.
- Use Ku-band DDC results to guide development of Ka-band DDC.
- Build prototypes using new low-thermal expansion materials to achieve thermal stability.
- Characterize amplitude and phase stability between –10 and 50 deg C in a thermal chamber.

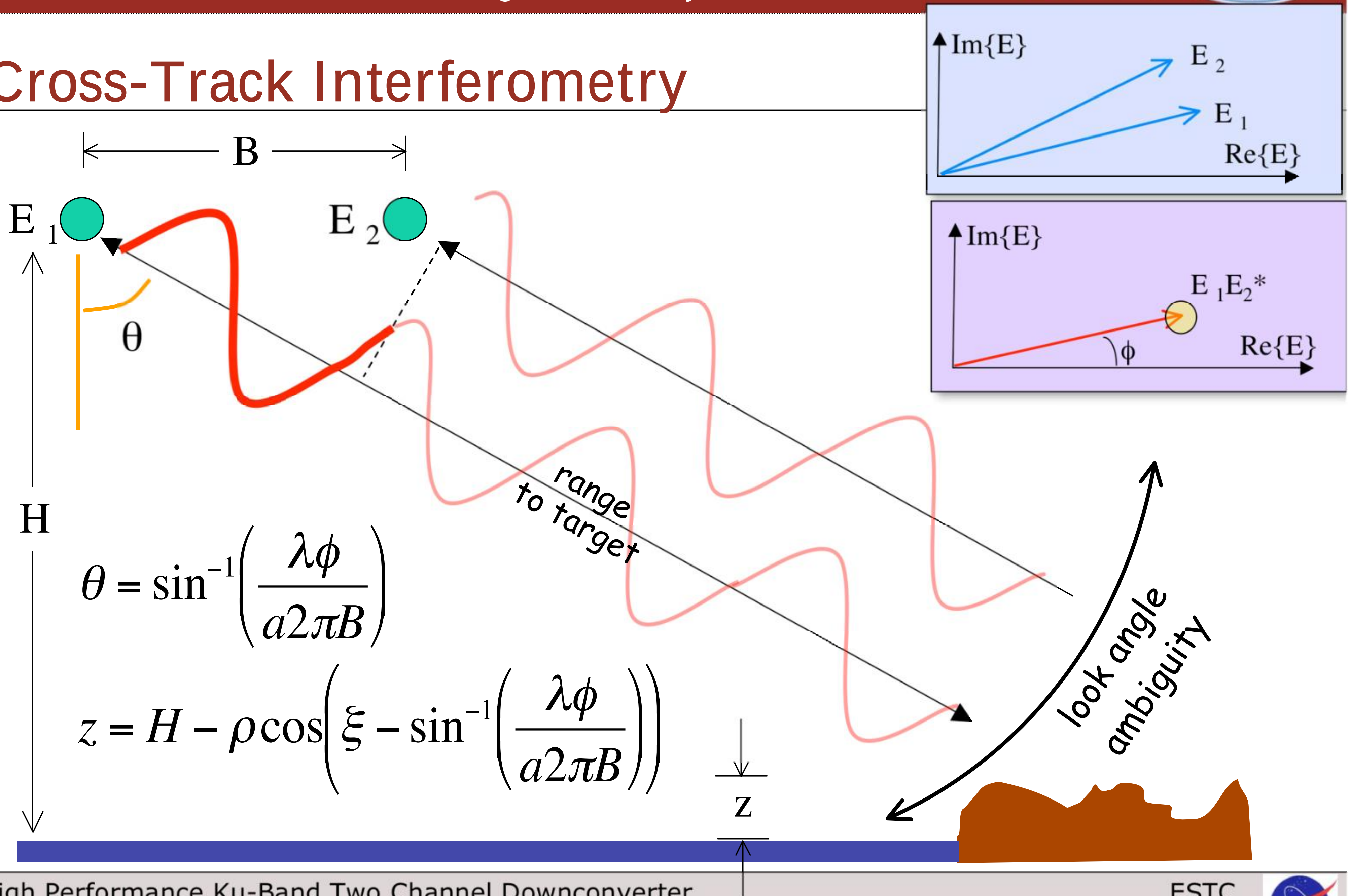
Key Milestones

• Conduct Ku-Band DDC Design Review	01/06
• Complete Ku-Band DDC Feedthrough Test	07/06
• Complete Ku-Band Functional Testing	11/06
• Complete Ku-Band Performance Report	05/07
• Conduct Ka-Band DDC Design Review	03/07
• Complete Ka-Band DDC Feedthrough Test	09/07
• Ka-Band Functional Report	11/07
• Deliver Final Report	08/08

Mission Scenarios

- Enabling Technology: High phase accuracy and low cross-talk two-channel Ku- and Ka-band downconversion to IF.
- Generic capabilities
  - precision polarimetry
  - precision interferometry (along-track and cross-track)
  - index of refraction studies for the atmosphere
- Airborne
  - compact side-looking interferometer for topographic and volumetric depth measurements
- Spaceborne
  - detailed characterization will provide key inputs for mission design and observing scenarios
  - Wide Swath Ocean Altimeter (WSOA)
  - Sea Ice and cold lands process satellites

Cross-Track Interferometry

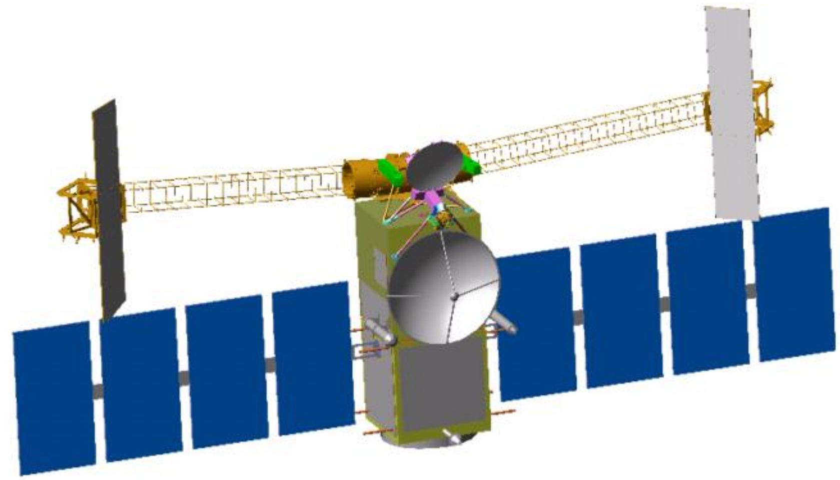


$$\theta = \sin^{-1}\left(\frac{\lambda\phi}{a2\pi B}\right)$$

$$z = H - \rho\cos\left(\xi - \sin^{-1}\left(\frac{\lambda\phi}{a2\pi B}\right)\right)$$

Phase Measurement Accuracy

WSOA, Ku-band 6.4m



$$\sigma_z^2 = \left(\frac{dz}{d\phi}\right)^2 \sigma_\phi^2 + \left(\frac{dz}{dB}\right)^2 \sigma_B^2 + \left(\frac{dz}{d\xi}\right)^2 \sigma_\xi^2 + \left(\frac{dz}{dH}\right)^2 \sigma_H^2 + \left(\frac{dz}{d\lambda}\right)^2 \sigma_\lambda^2 + \left(\frac{dz}{d\rho}\right)^2 \sigma_\rho^2$$

A_ϕ, phase noise

A_B, baseline length

A_ξ, baseline tilt

A_H, altitude

A_λ, wavelength stability

A_ρ, target range

Design Specifications

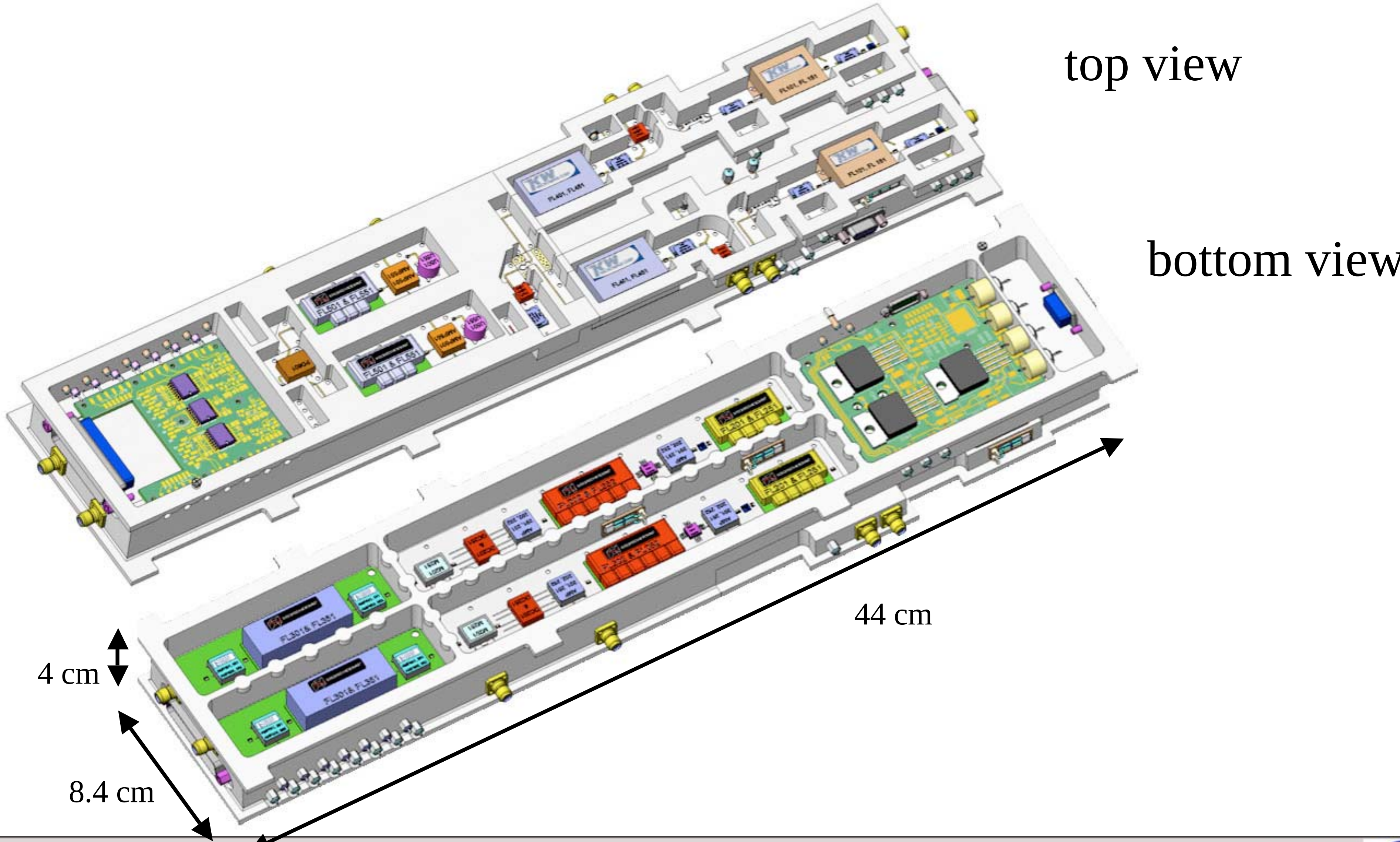
Design Constraint	Ku-band DDC	Ka-band DDC
Signal Bandwidth	20 MHz	20 MHz
Effective Noise Bandwidth	< 30 Mhz	< 30 MHz
Input Frequency Range	13275 – 13295 MHz	34975 – 34995 MHz
Operating Temperature	-10 to 50 degrees C	-10 to 50 degrees
Noise Figure	< 4.5 dB	< 4.5 dB
Output Frequency Range	5-25 MHz	5-25 MHz
Channel to Channel Isolation	> 80 dB	> 80 dB
Input/Output VSWR	< 1.5:1	< 1.5:1
Relative Channel to Channel Phase Stability	0.050 degrees RMS over BW	0.050 degrees RMS over BW
Receiver Phase Variation over Best Quadratic Fit	3 deg RMS over BW	3 deg RMS over BW
Receiver Amplitude Variation	2 dB over BW	2 dB over BW
Receiver Amplitude Variation over Best Linear Fit	0.3 dB RMS over BW	0.3 dB RMS over BW
Input Signal Range	-100 to –65 dBm	-100 to –65 dBm
DDC End to End Gain	65 to 70 dB	65 to 70 dB
Image Rejection	> 30 dB	> 30 dB

Approach

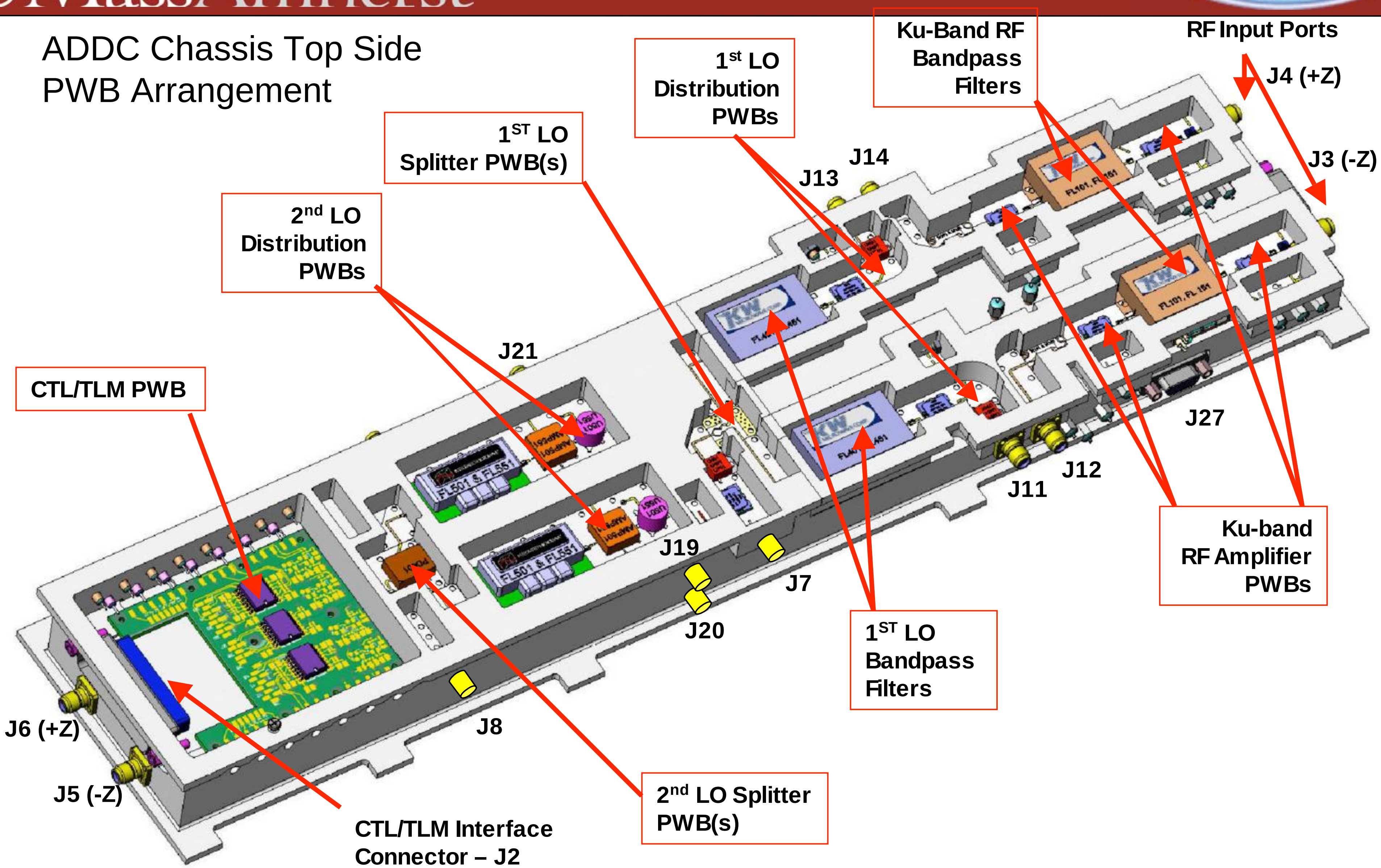
- Breadboard Design
  - use parts and design strategy that is as close to flight quality as possible
  - design for low power, low mass and robust performance over large temperature range

- Testing and Modeling
  - design testing and modeling environment where theoretical tools and physical measurements can inform the design process

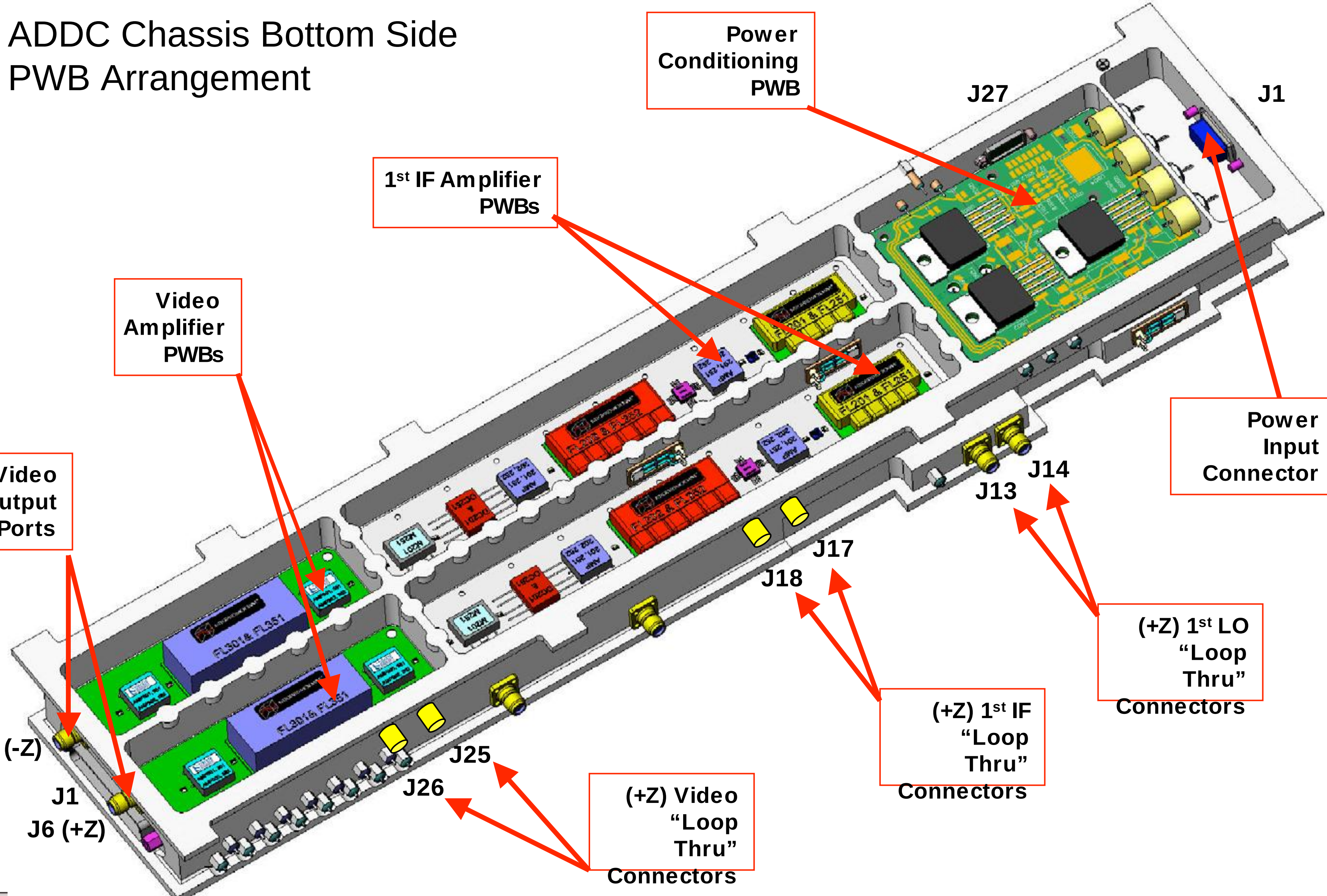
Current Mechanical Layout



ADDC Chassis Top Side PWB Arrangement



ADDC Chassis Bottom Side PWB Arrangement

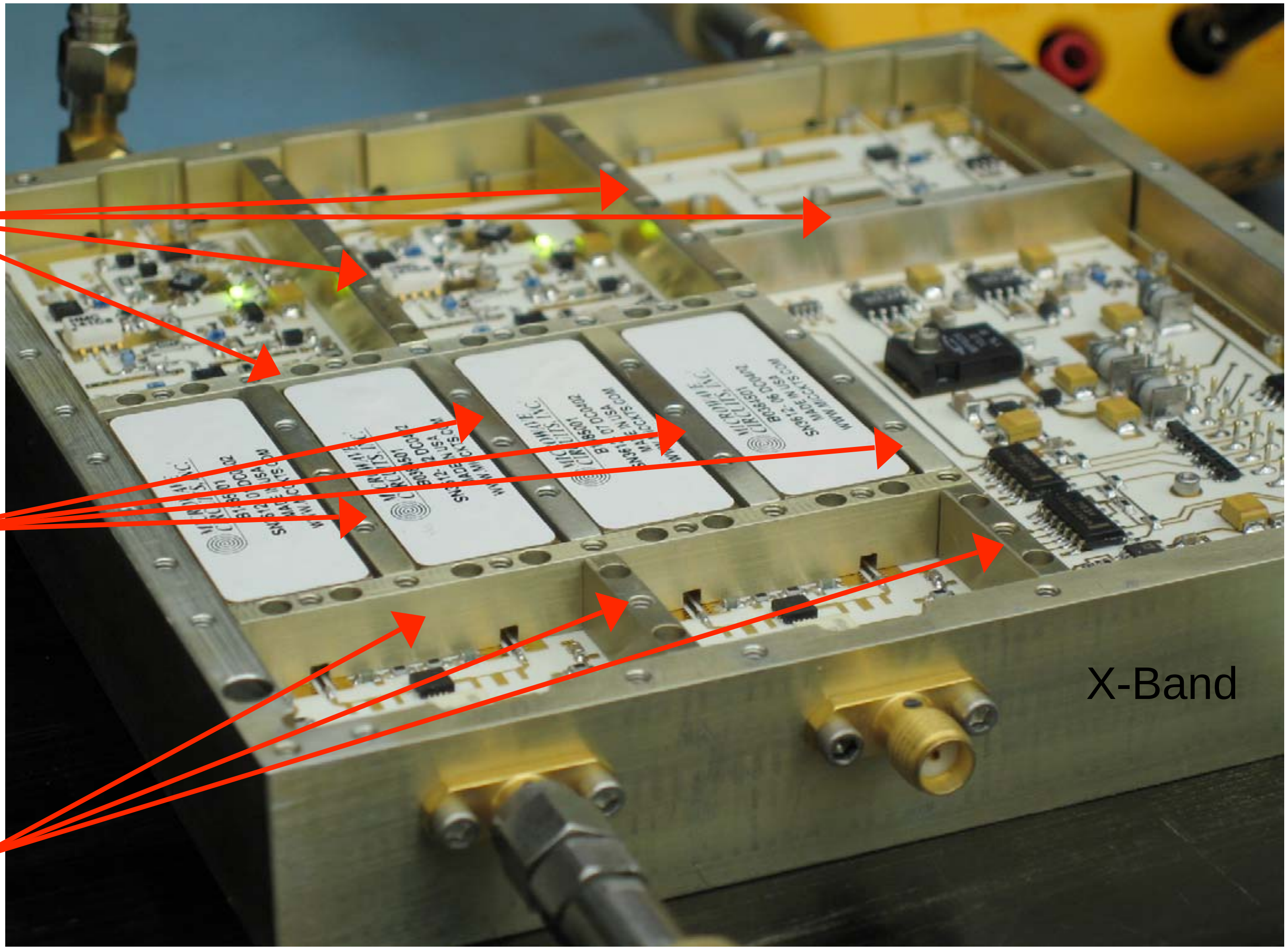


Existing Example of Drop-In Walls

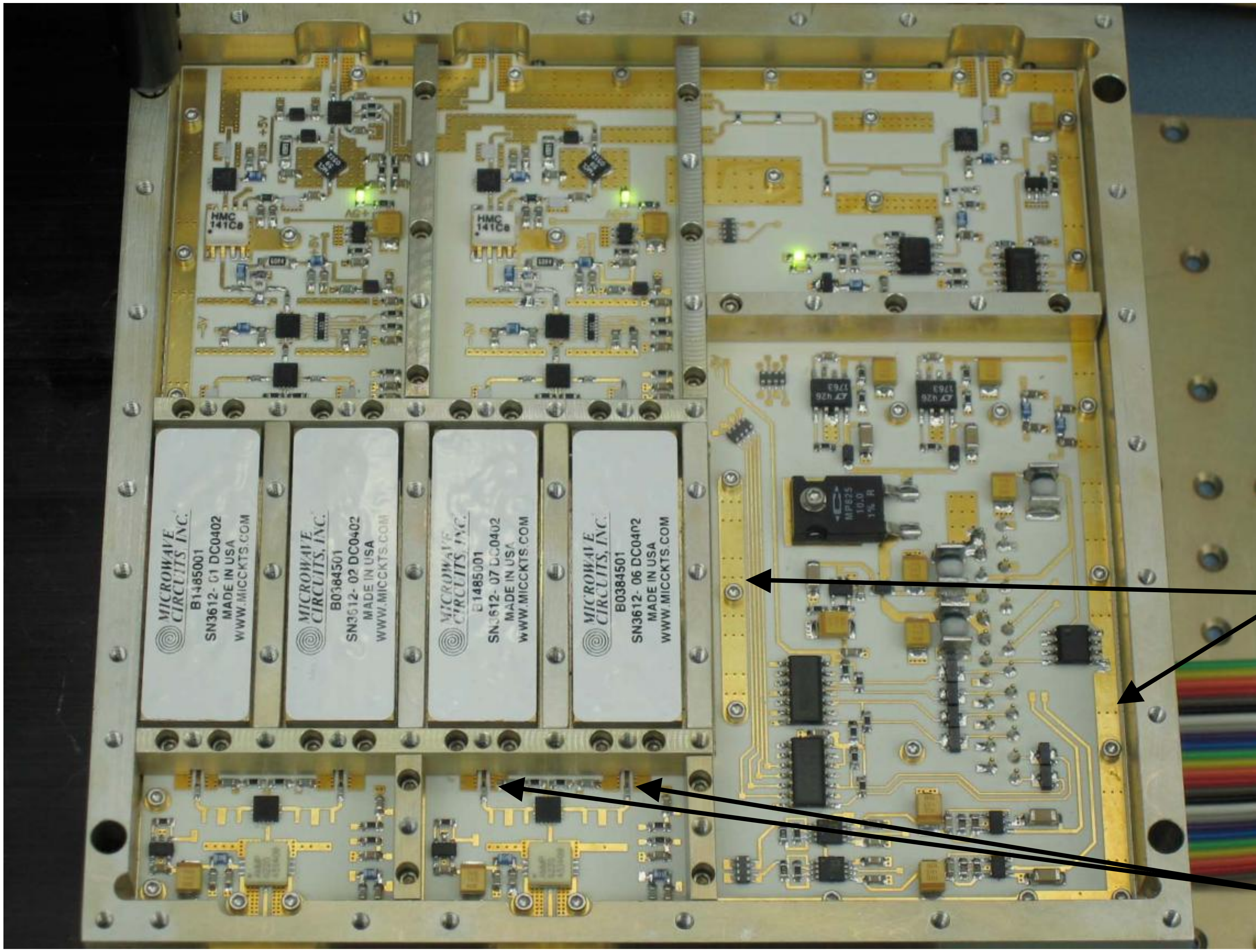
Drop-In
Cavity Walls

Fixed
Cavity Walls

Drop-In
Cavity Walls



DSN Array "XCON" Module (courtesy: Mike Ciminera)



via grounding walls

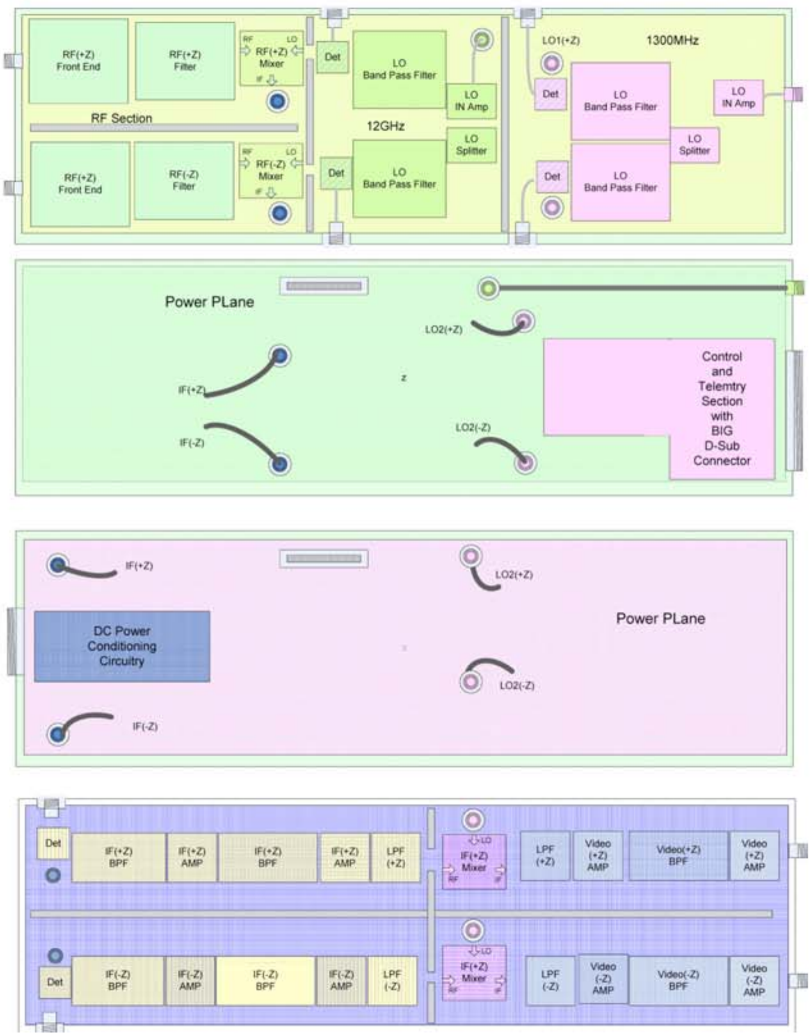
microstrip feedthroughs

top view

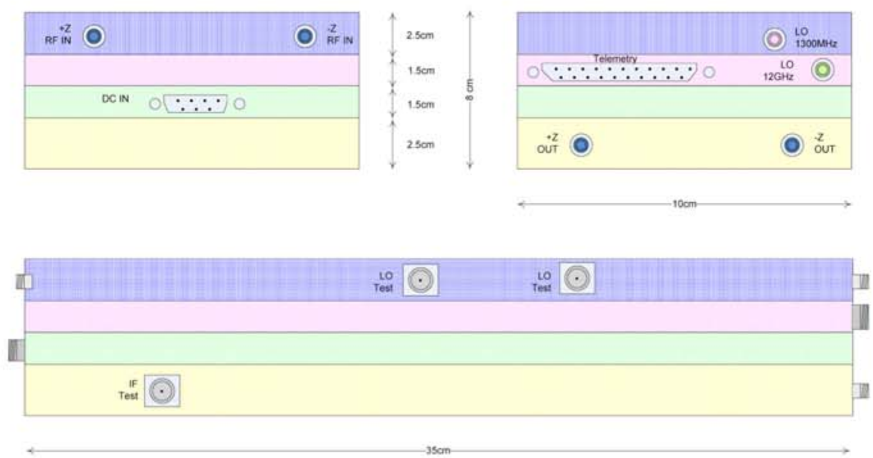
Clam Shell Design

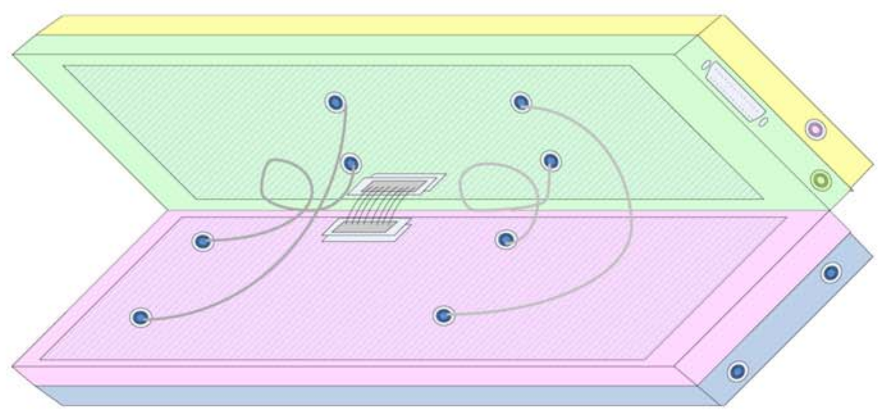
TOP VIEW

layers are presented from top to bottom



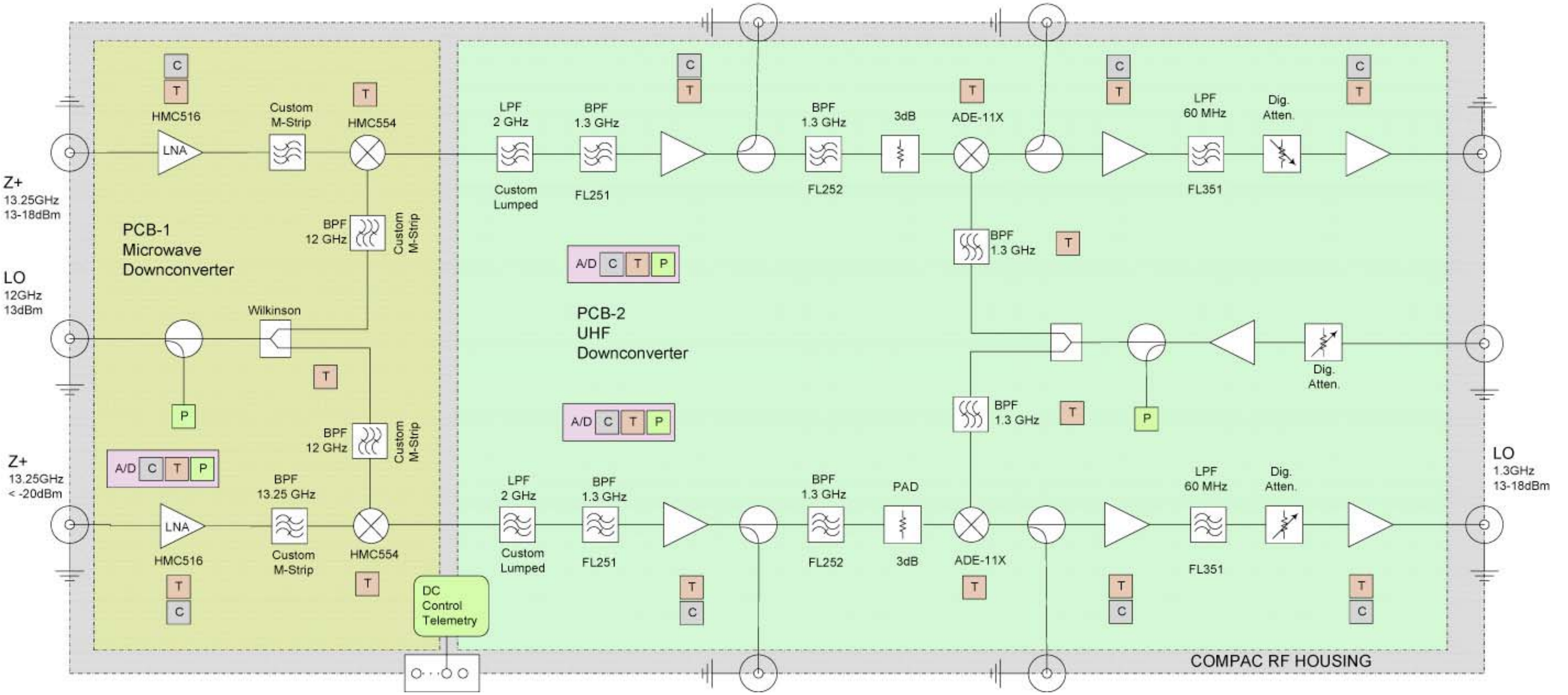
SIDE VIEW





3D view

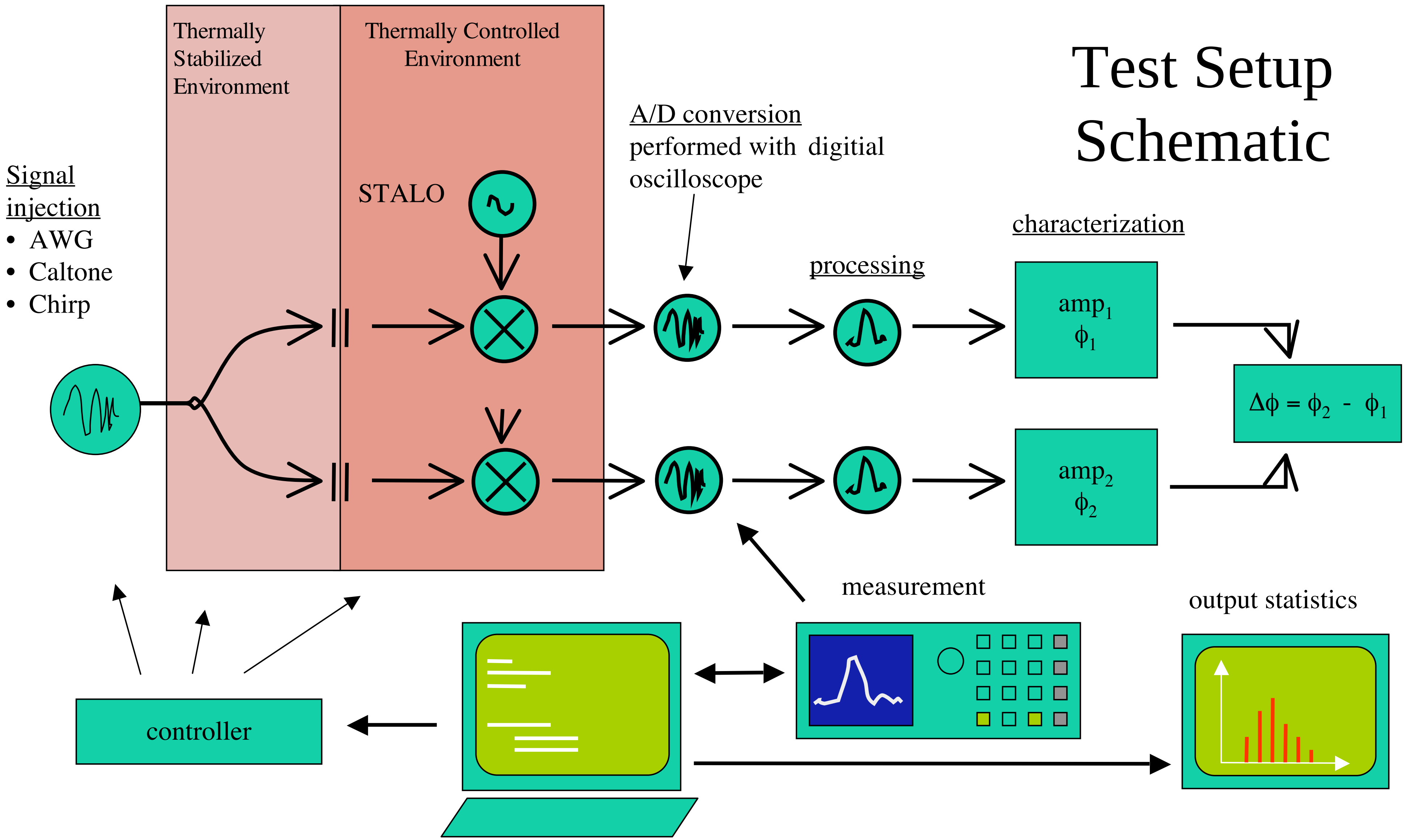
Single Surface, 6-Layer Layout



Testing

- Multiple downconversion stages and requirements for high measurement precision make it difficult to use standard test equipment
- Direct control over measurement accuracy and per measurement duration
- Ability for providing a variety of statistical measures and indicators of significance
- Direct access to measured data allows careful analysis of measurement anomolies (kazoo).

Test Setup Schematic



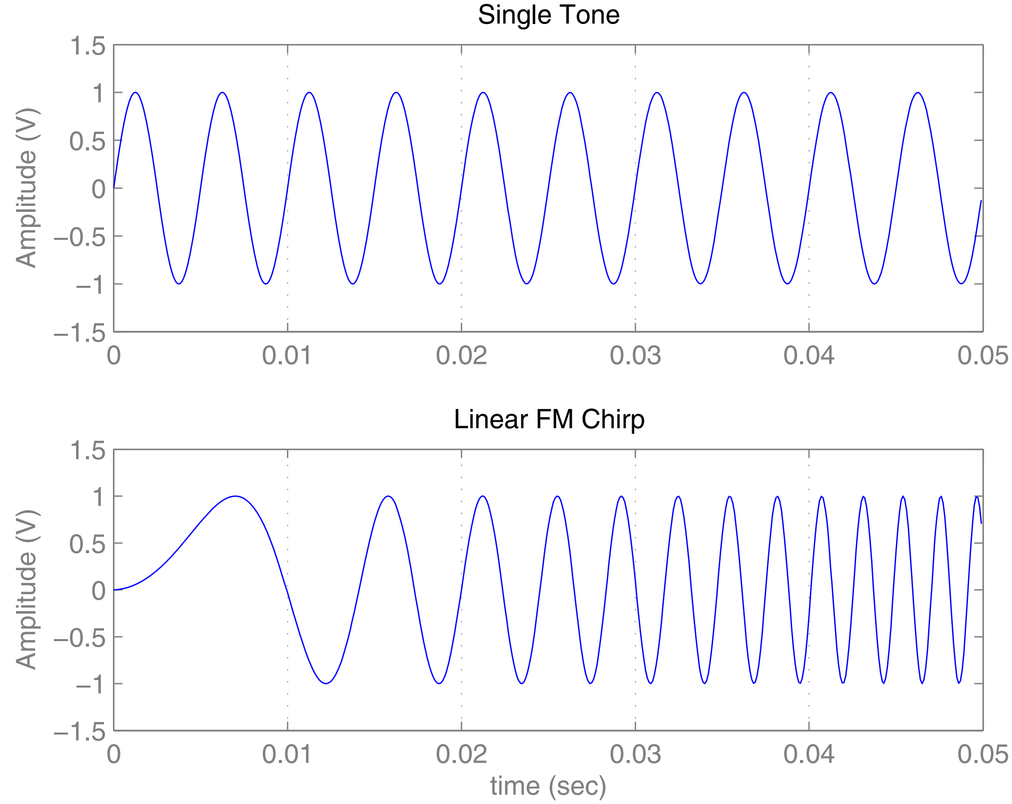
Input Signals

- currently relying on two generic waveforms input from an AWG / signal generator
  - single-tone sinusoid

    $$A\cos\left(2\pi ft+\varphi\right)$$

  - linear chirp

    $$A\cos\left(2\pi f_0 t+\pi\beta t^2+\varphi\right)$$



Maximum Likelihood Estimation

- Input signal linearized about expected parameter values

$$\underline{S} = H\underline{\theta} + \underline{V}$$

- The estimate for θ is given by

$$\underline{\hat{\theta}}_{ML} = \max_{\underline{\theta}} \left\{ p\left(\underline{S} \middle| \underline{\theta}\right) \right\}$$

- with the pdf

$$p\left(\underline{S} \middle| \underline{\theta}\right) = \frac{1}{\sqrt{(2\pi)^N |R|}} \exp\left[-\frac{1}{2} \left(\underline{S} - H\underline{\theta}\right)^T R^{-1} \left(\underline{S} - H\underline{\theta}\right) \right]$$

Contd...

- The likelihood function that we want to minimize is

$$L = \left(\underline{S} - H\underline{\theta}\right)^T R^{-1}\left(\underline{S} - H\underline{\theta}\right)$$

- familiar ML solution gives

$$\underline{\hat{\theta}}_{ML} = \left(\underline{\underline{H}}^T \underline{\underline{R}}^{-1} \underline{\underline{H}}\right)^{-1} \underline{\underline{H}}^T \underline{\underline{R}}^{-1}\left(\underline{S} - \underline{\underline{H}}\underline{\theta}_0\right) + \underline{\theta}_0$$

- H is obtained by Taylor series expansion

$$S(\theta) \approx S(\theta_0) + \frac{\partial S(\theta)}{\partial \theta}(\theta - \theta_0)$$

Cramer-Rao Lower Bound for chirp estimators

- Phase estimate

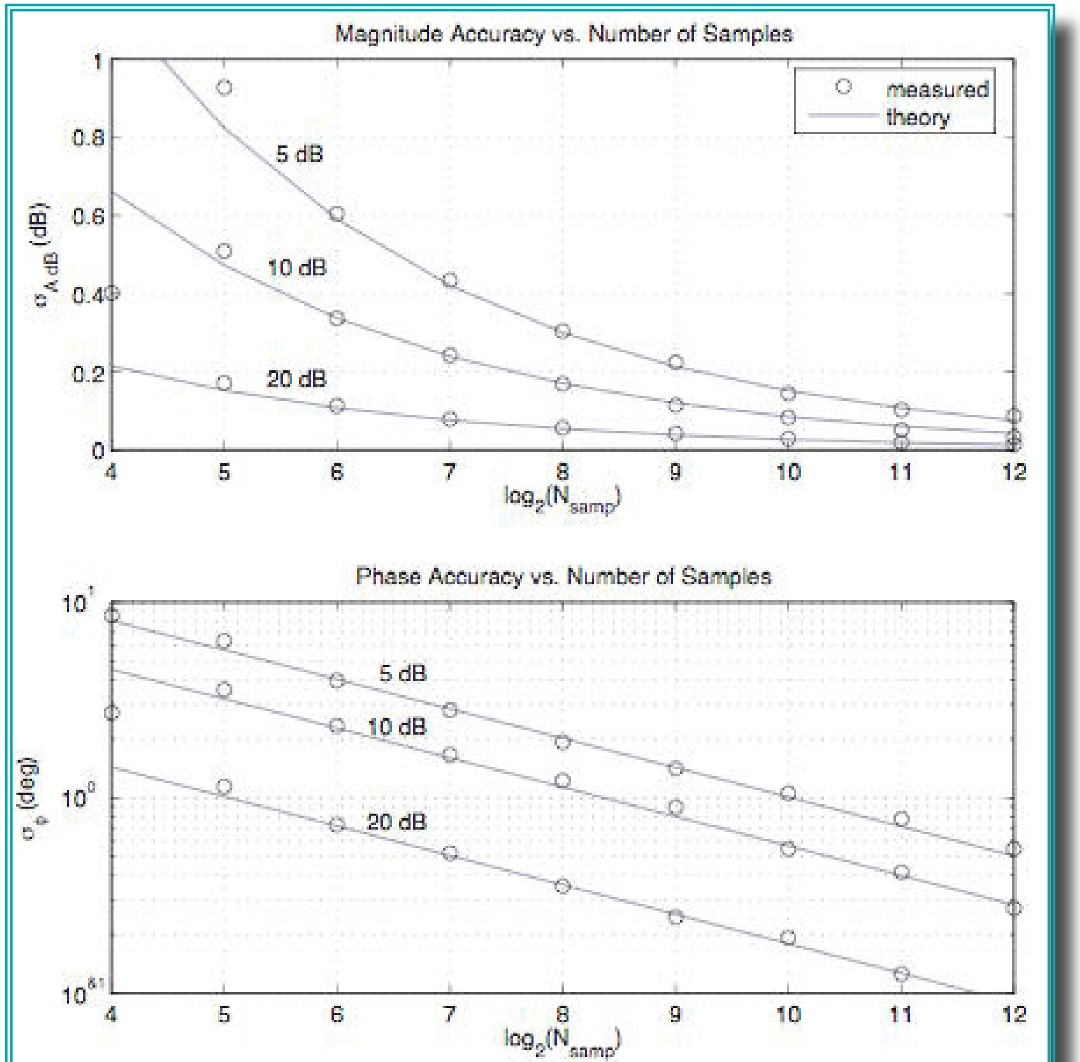
$$\sigma_{\varphi}^{2} \geq \frac{1}{N(SNR)}$$

- Frequency estimate

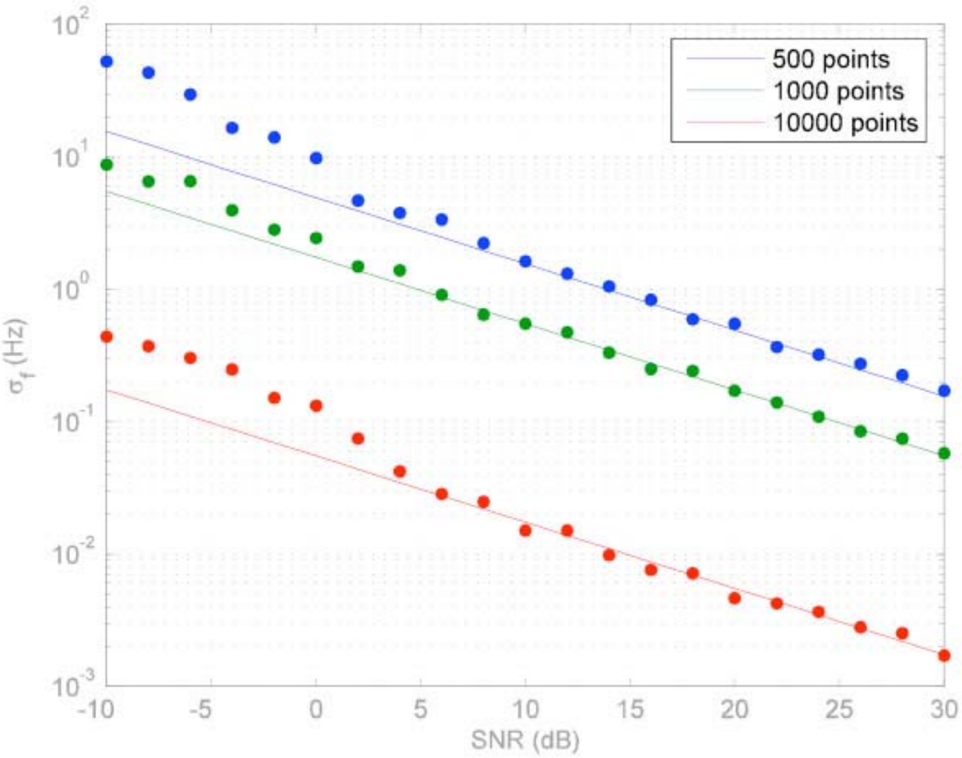
$$\sigma_{f}^{2} \geq \frac{3}{\pi^{2}(SNR)N^{3}\Delta T^{2}}$$

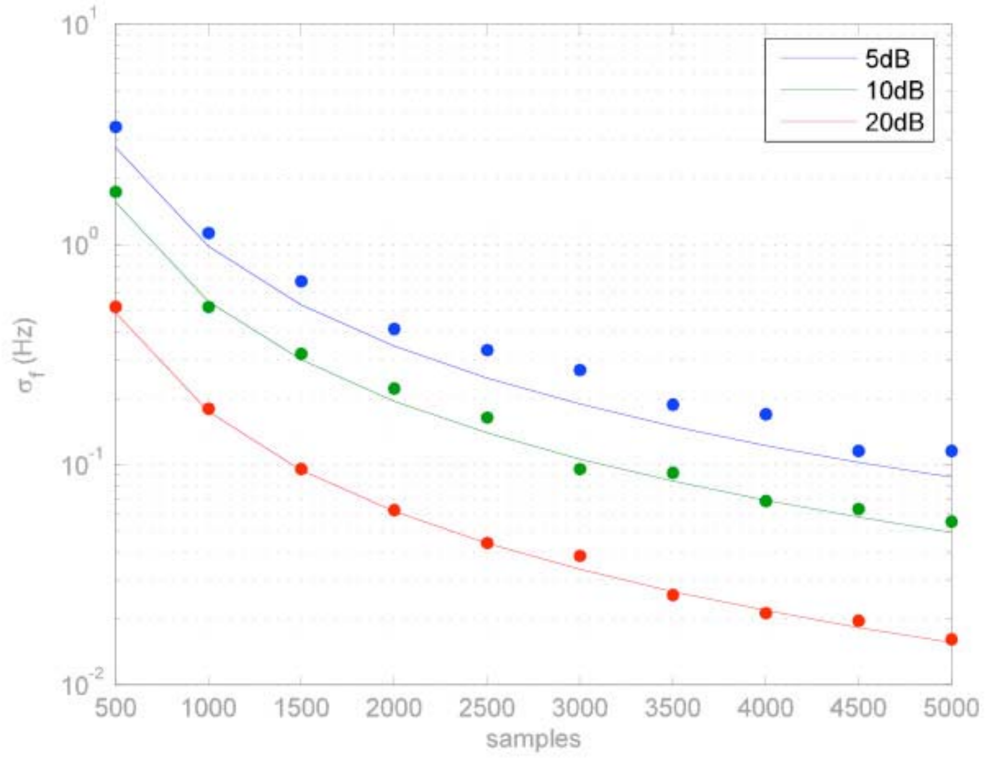
- Sweep rate estimate

$$\sigma_{\beta}^{2} \geq \frac{90}{\pi^{2}(SNR)N^{5}\Delta T^{4}}$$

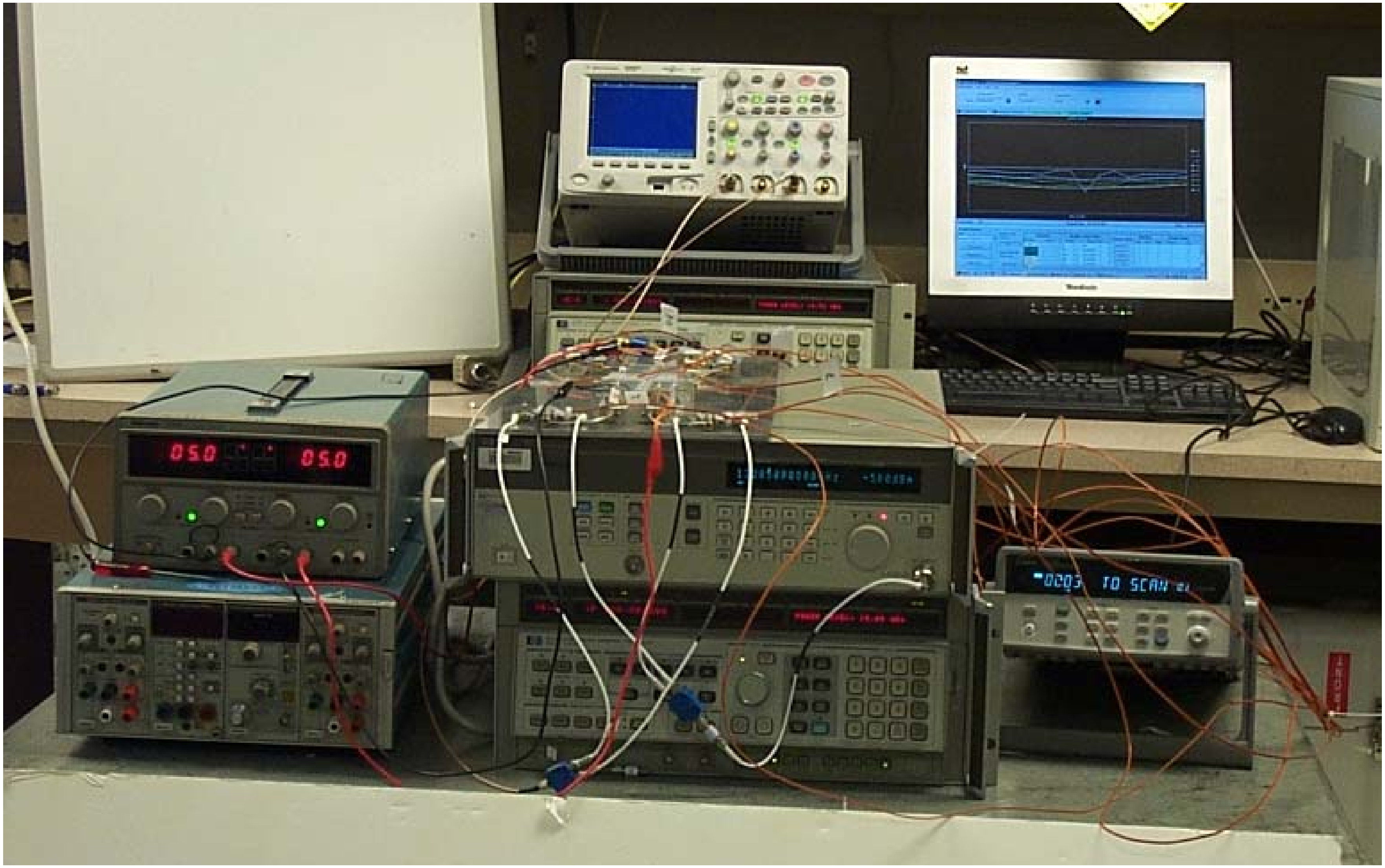


Evaluation of single tone frequency estimate against SNR and number of samples.

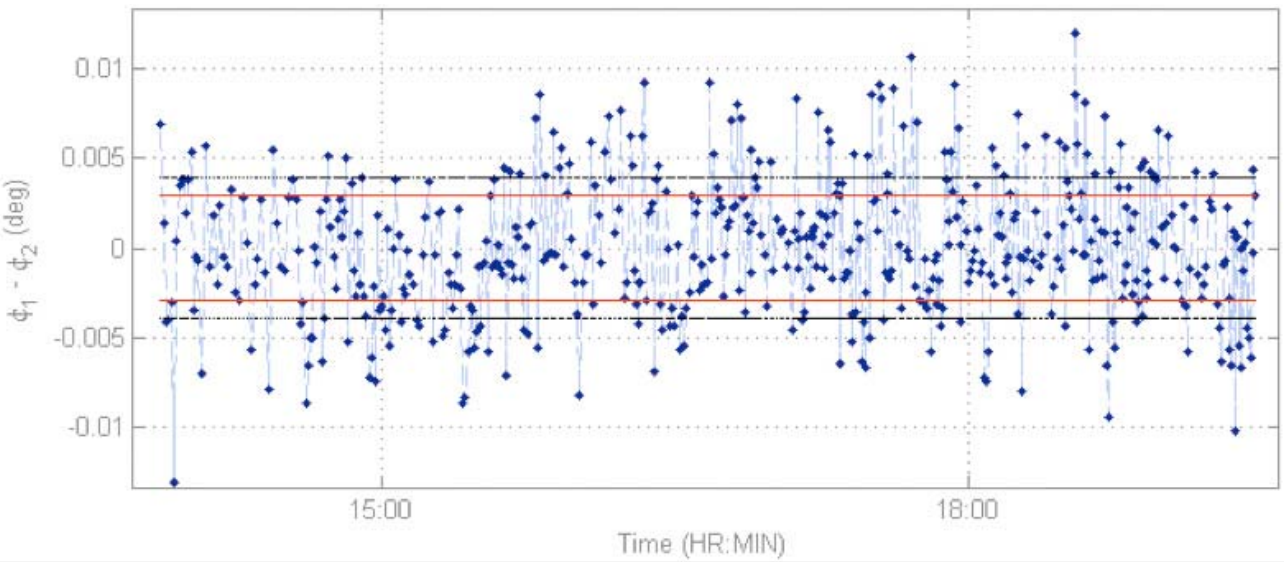


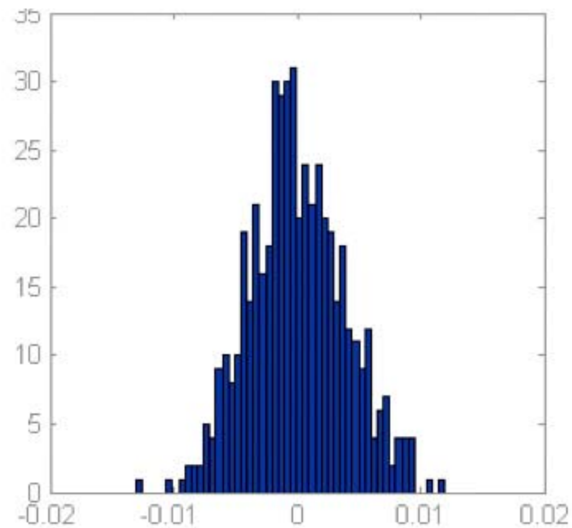


Test Setup



Test System Accuracy





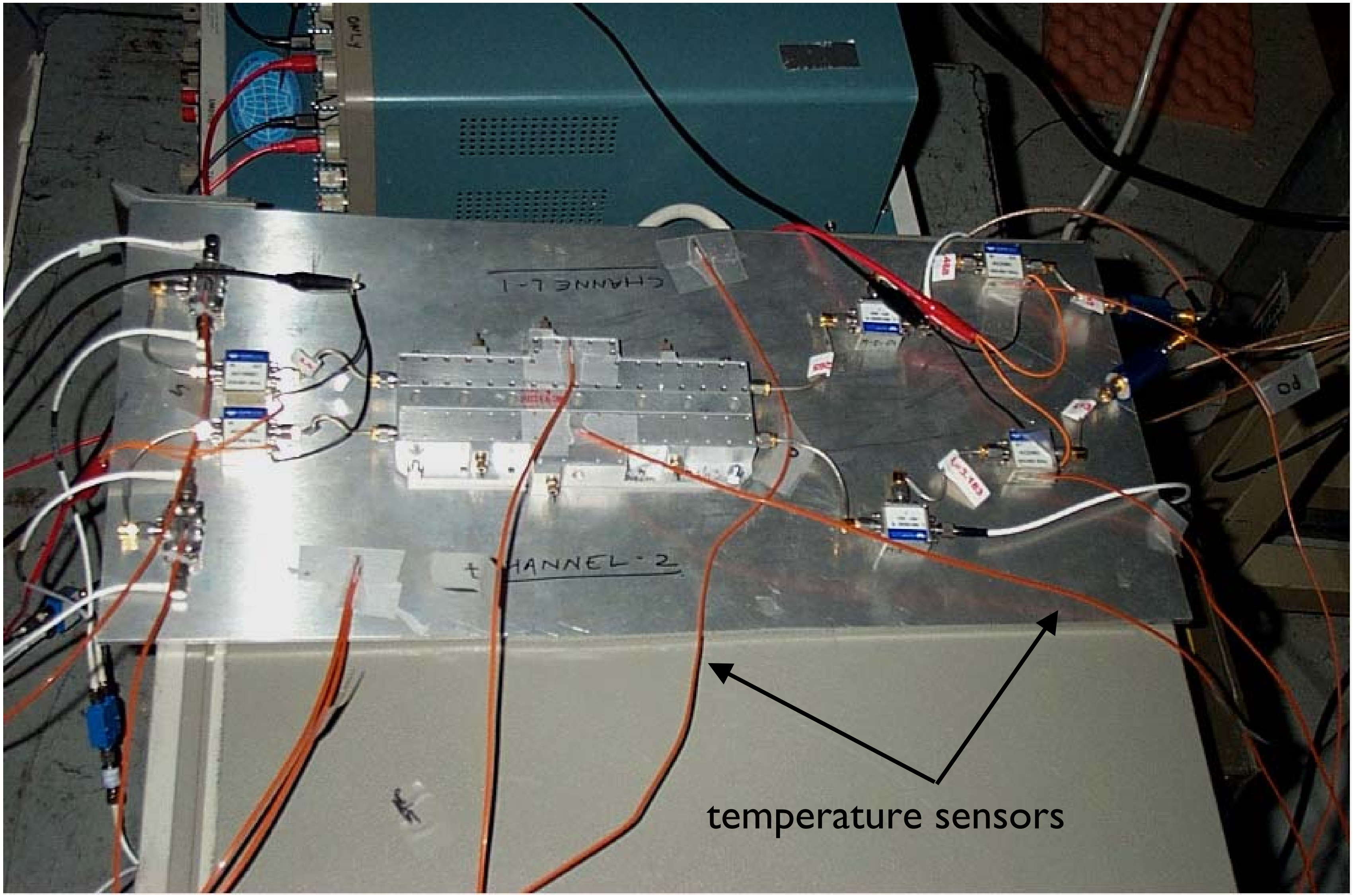
σ_ϕ (CRLB) = 3 mdeg (30 dB SNR; 400,000 samples)

σ_ϕ (observed) = 3.5 mdeg → accept the null hypothesis,

H0: there is no phase difference

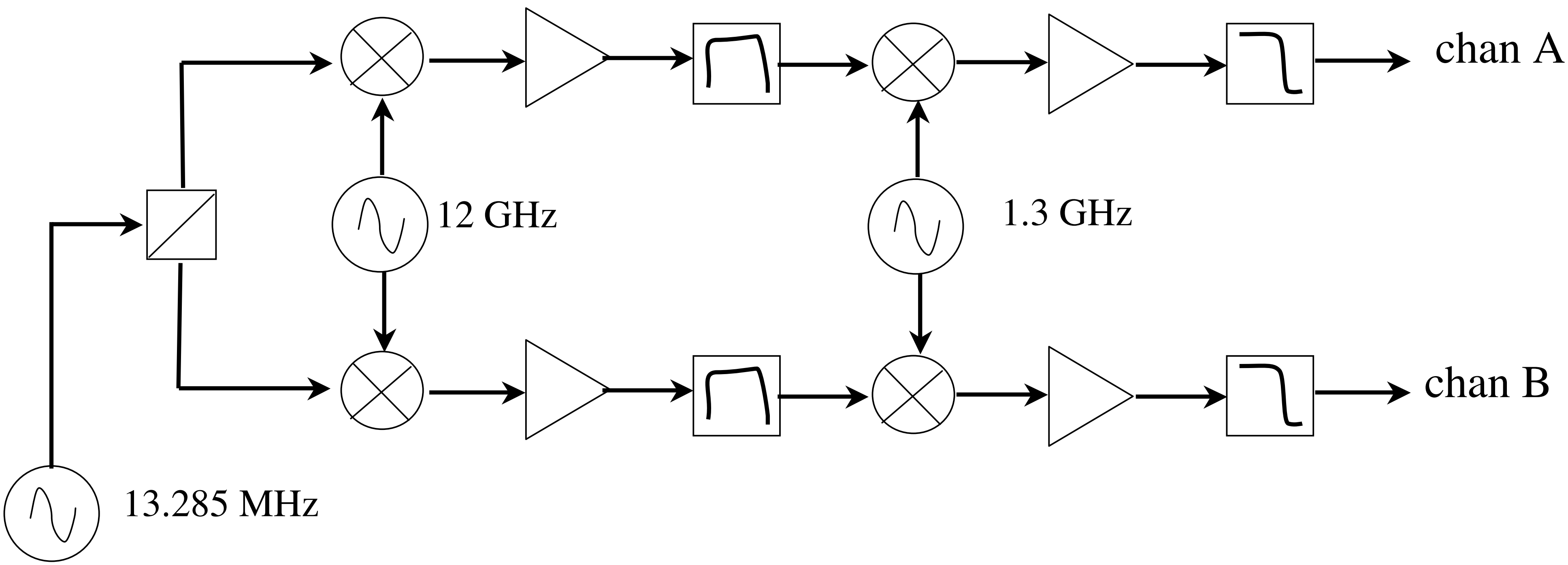
Two-Channel Breadboard

Ku-band input

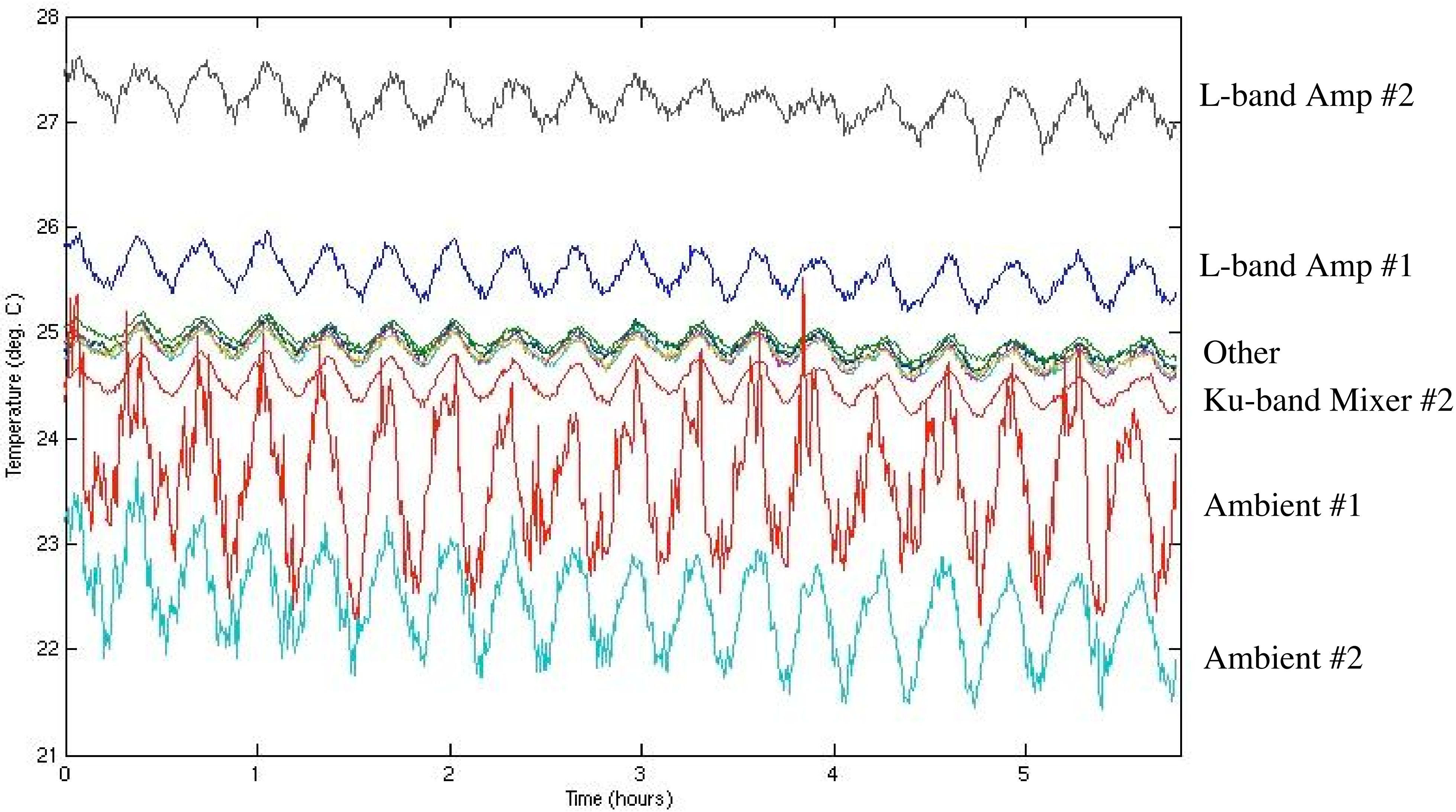


IF output (5-25 MHz)

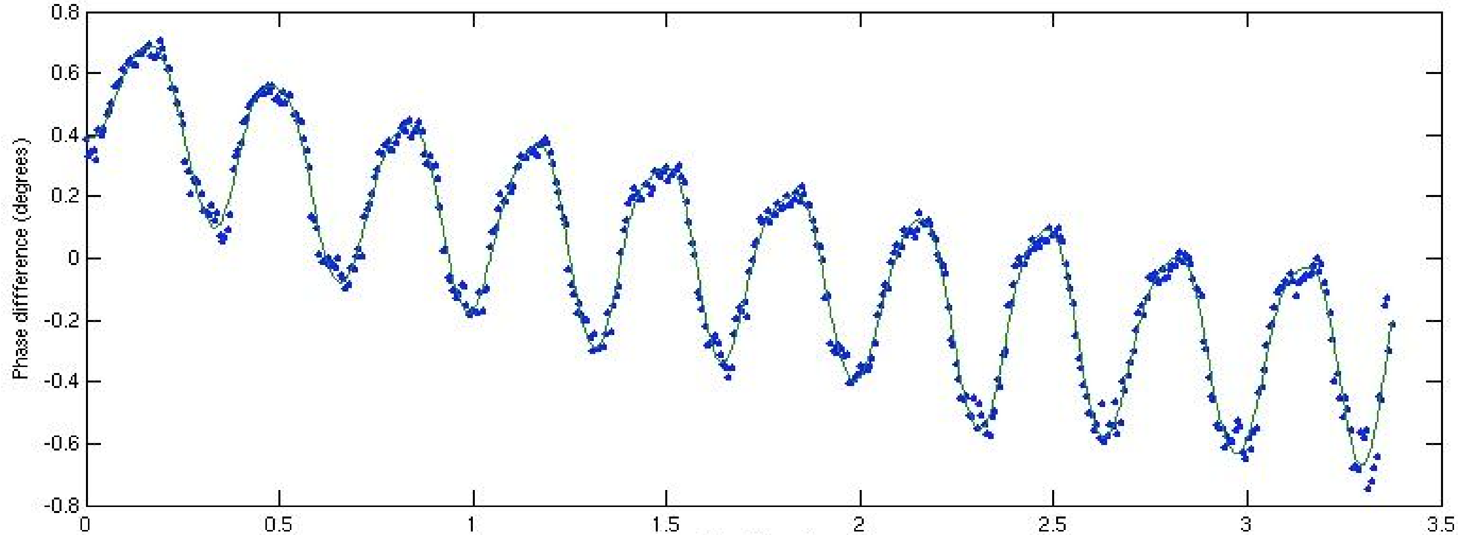
Simple Block Diagram



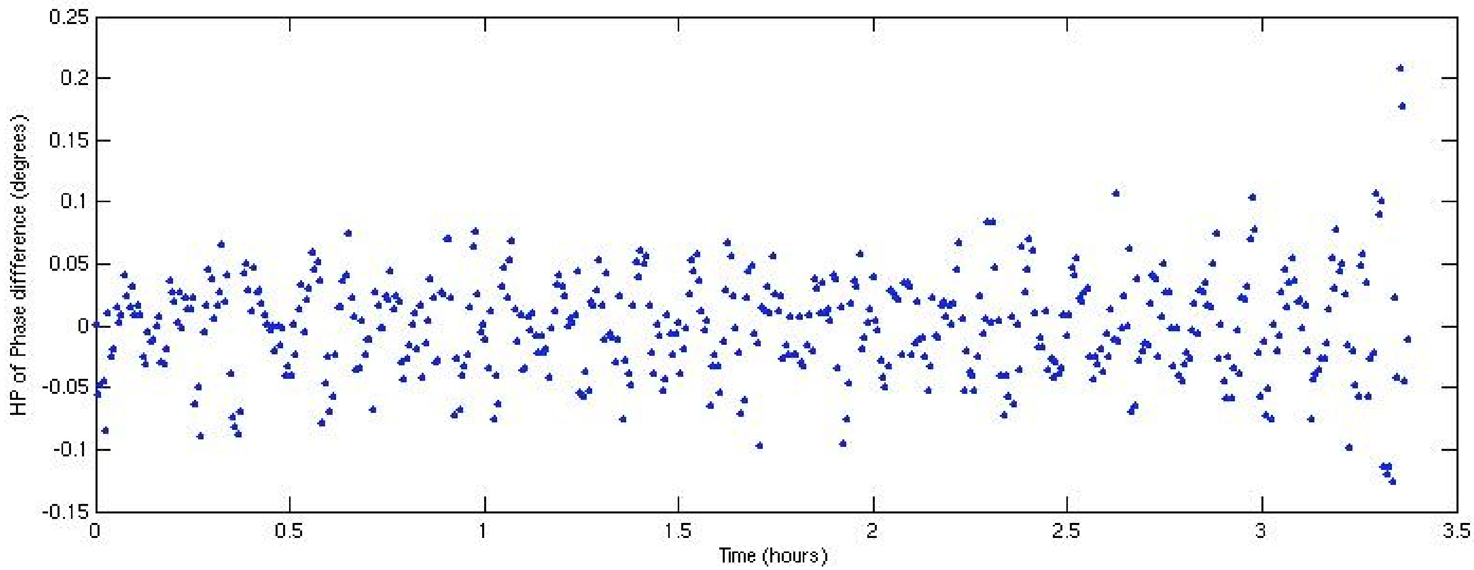
Thermal Profiles Over Time



A Simple Low-Pass Filter & Residuals



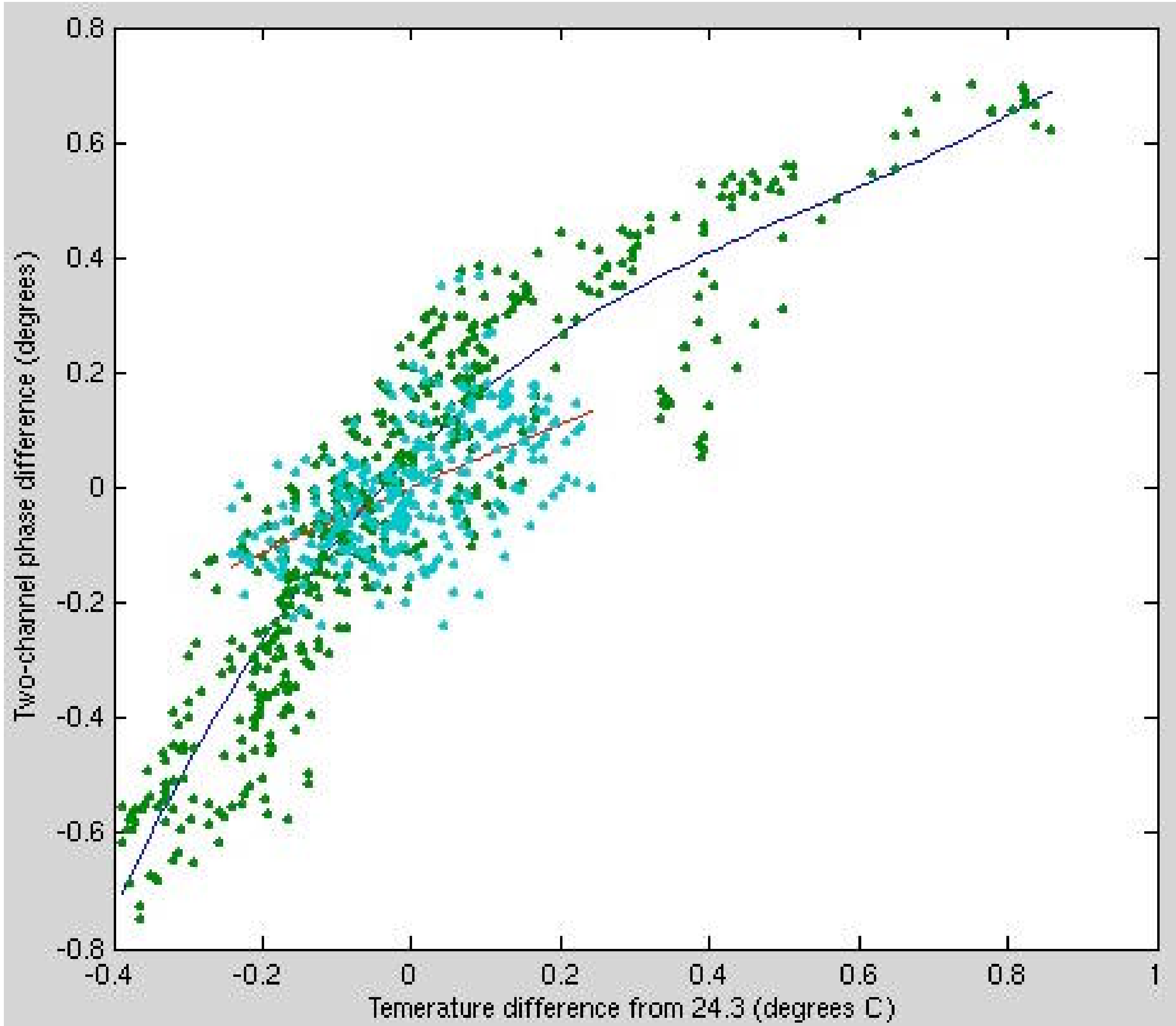
low pass filter to remove slow variations likely due to temperature swings



remaining error estimate of system after temperature stabilizing

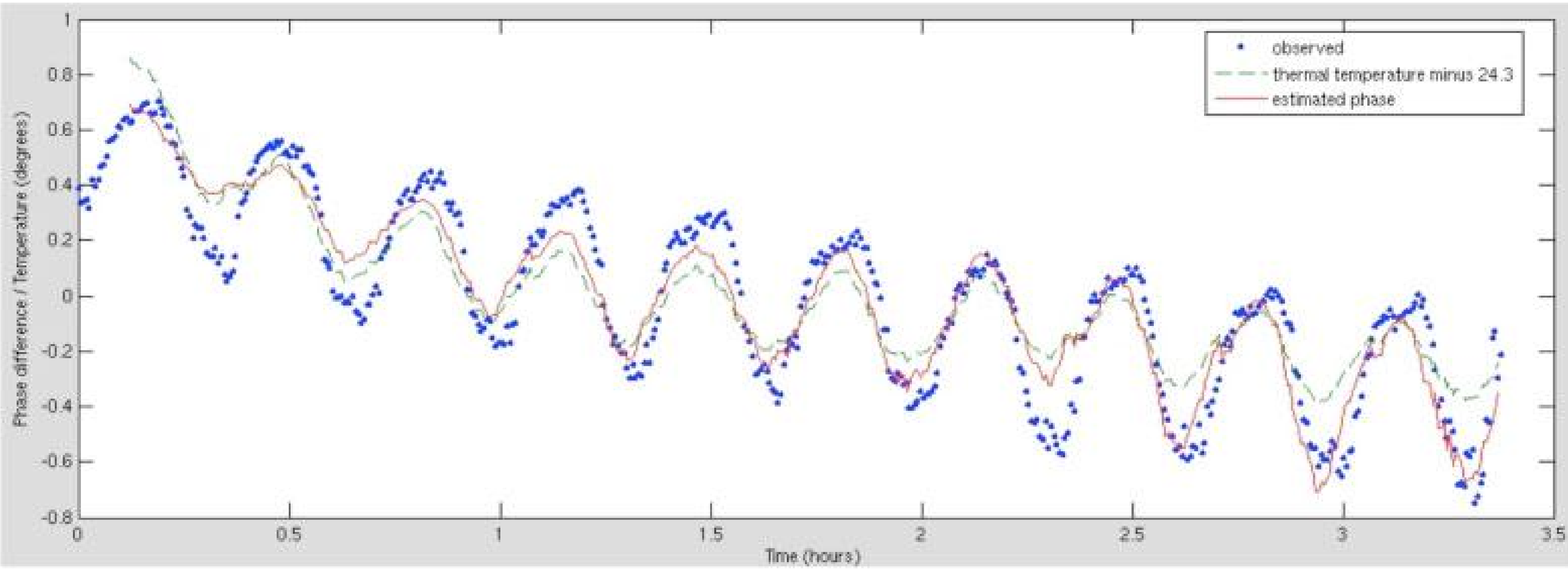
st. dev. = 0.04º

Temperature dependence of the phase difference

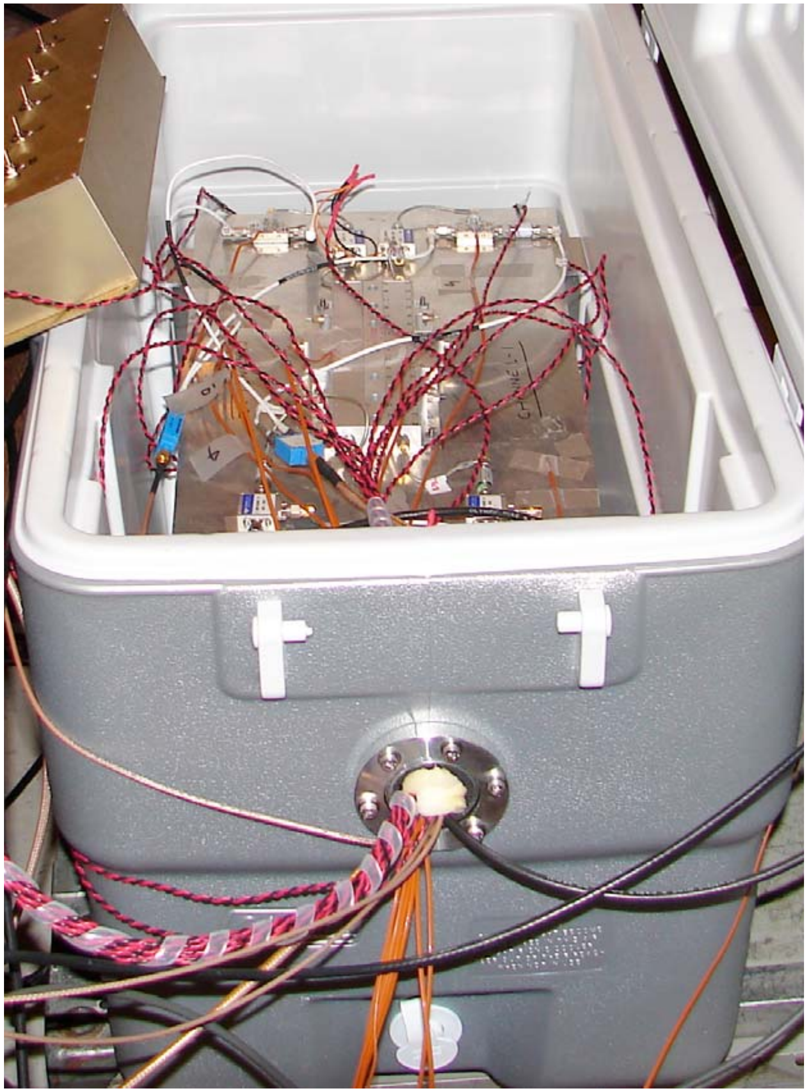


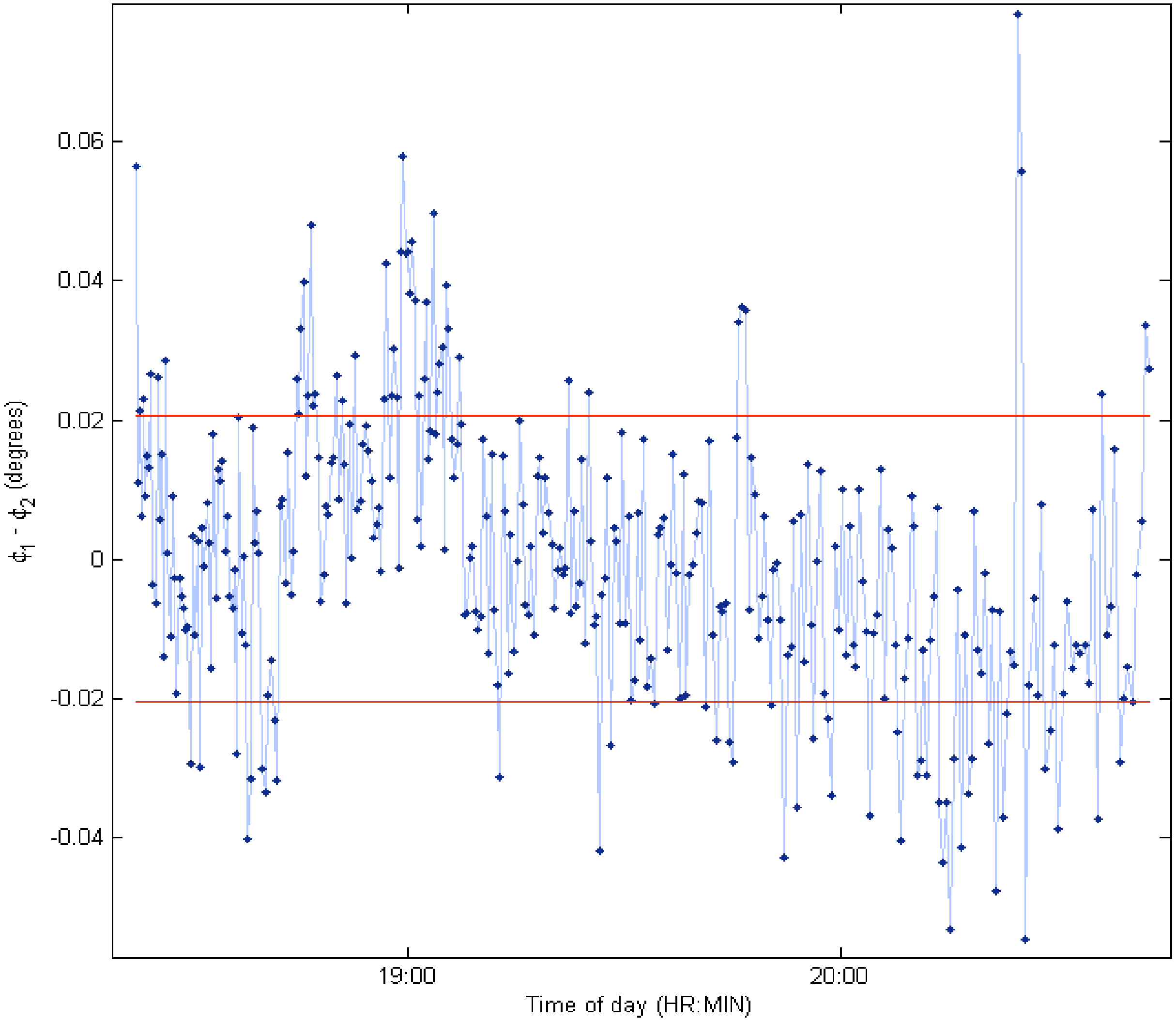
- A simple polynomial model that directly relates temperature to measured phase difference
- Encouraging in that phase difference is related to temperature and is relatively consistent
- Efforts ongoing to both control temperature and perform better characterization.

Phase Difference, Temperature, and Best Fit Model



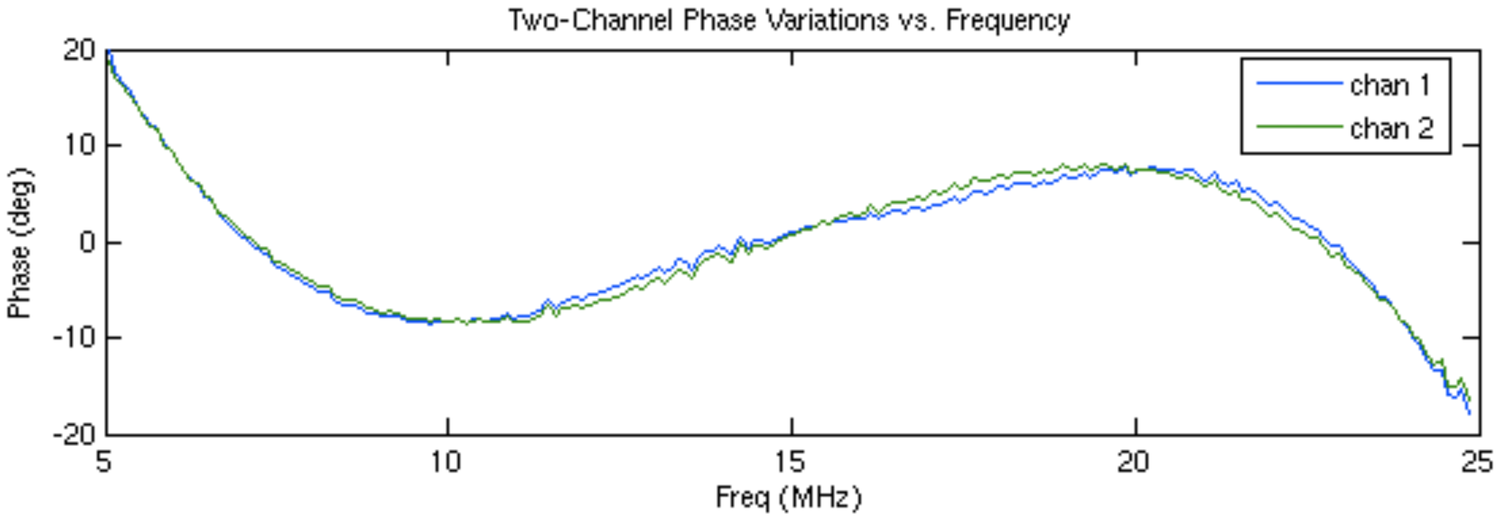
Thermal Testing

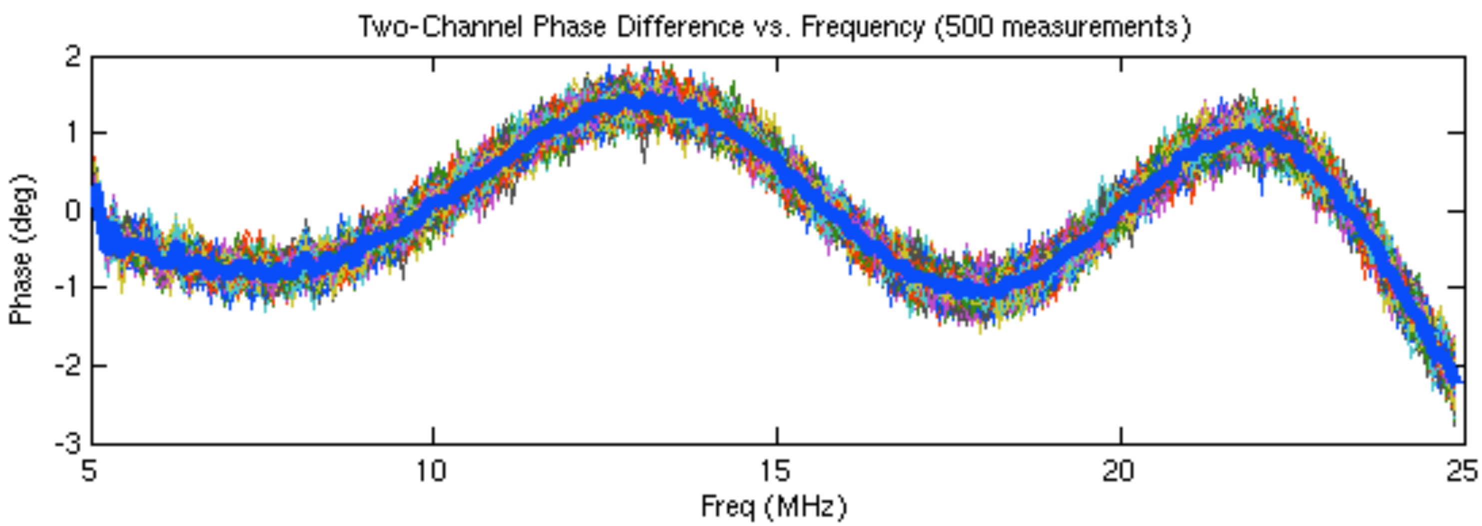




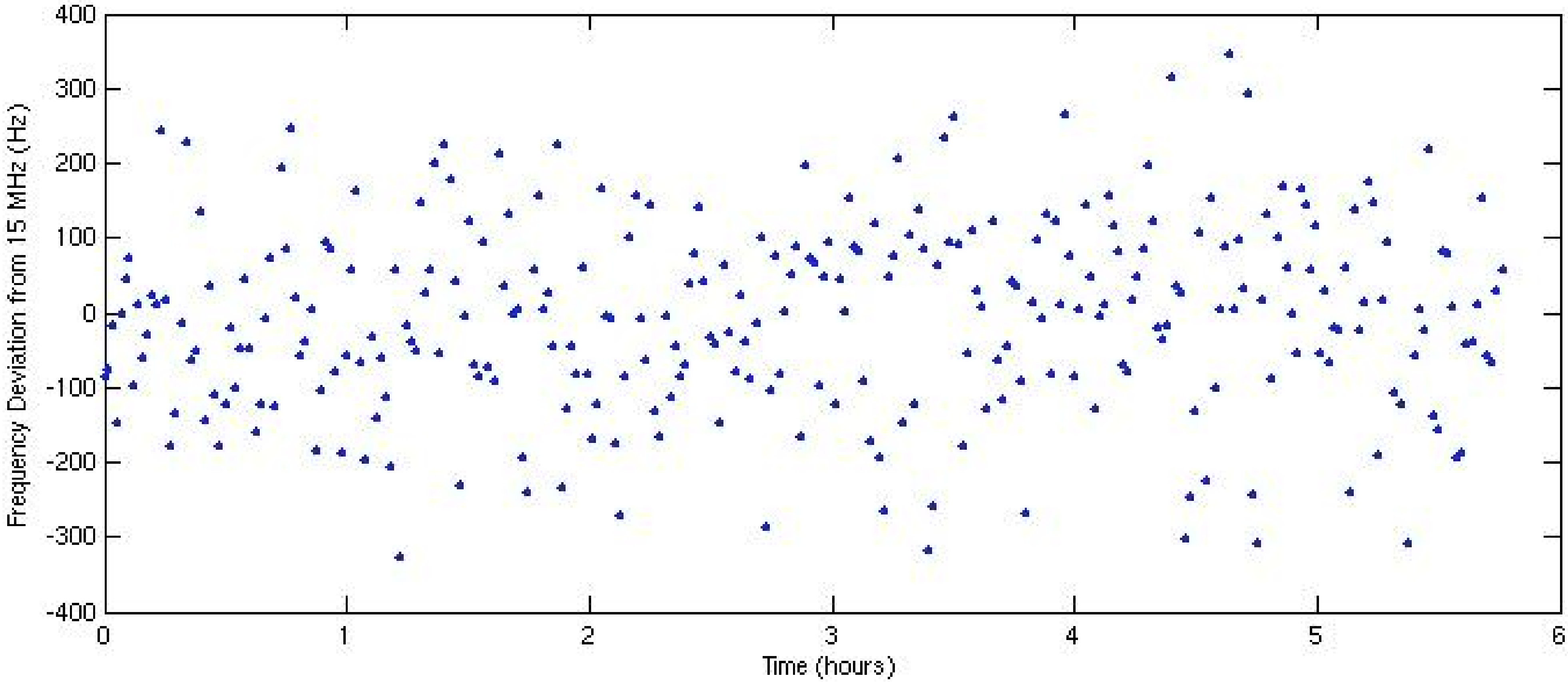
Phase (≥ 3rd order) over Bandwidth

≥





Frequency Stability



st. dev = 130 Hz; Allan variance, σ^2_y = 7e-11

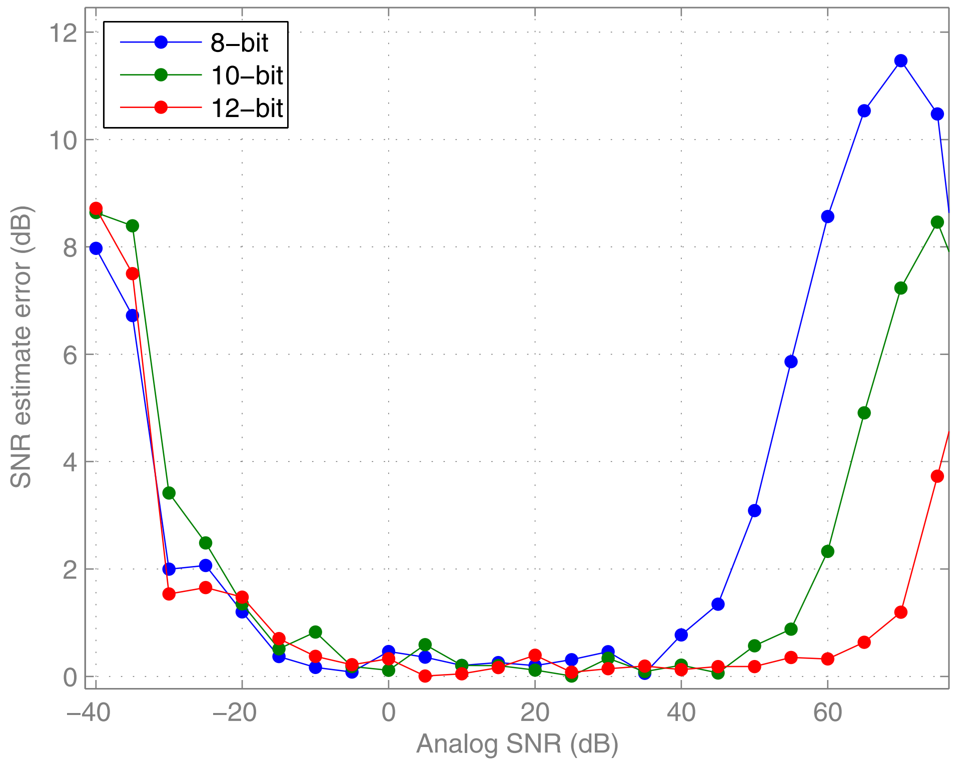
Hitting the quantization error limit

- Inversion of CRLB helps estimate SNR.

$$SNR = \frac{1}{\sigma_\varphi^2 N}$$

- Observe effects of quantization

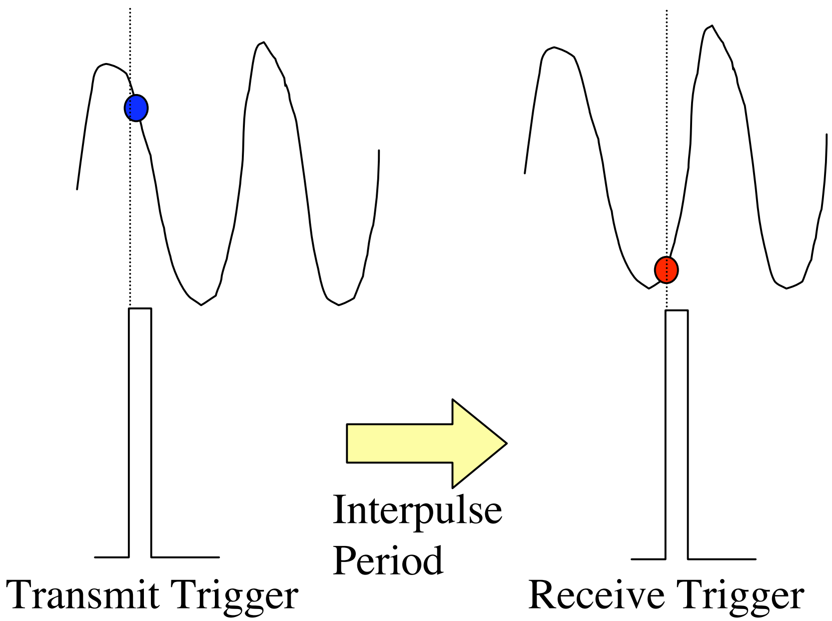
$$SNR_{quant} = 6q + 1.8 \quad dB$$



Testing Jitter and Timing Drift Requirements

APPROACH

- Inject a stable signal into the system
- Monitor phase of digitized samples
- Convert to estimates of timing drift and interpulse jitter



Conversion of time drift to phase

	1.6 nSec	0.026 nSec
10 MHz	5.7°	0.005°
13.286 GHz	~8000°	124°

Flexing the Thermal Environment

Manufacturer: Temptronic

TP04300A

Mobile Temperature System for testing components, parts, hybrids, modules, subassemblies and printed circuit boards at precise temperature.

TEMPERATURE PERFORMANCE AND AIRFLOW CAPACITY

Temperature Range:[1,3]	-80° to +225°C (60 Hz System) -75° to +225°C (50 Hz System)
Typical Temperature Transition Rate (air)[1,2]	-55° to +125°C: approx. 10 seconds or less[2] +125° to -55°C: approx. 10 seconds or less[2]
System air flow output	2.4 l/s to 9 l/s (5 to 18 scfm) CONTINUOUS
Temperature accuracy	1.0°C (when calibrated against NIST transfer standard)
Temperature set, display and resolution	± 0.1°C
Temperature Control:	
DUT Sensor Ports	Internal diode, Type T and Type K Thermocouple and 100 ohm Platinum RTD
DUT Control	Control to within ± 0.1°C; SELF-TUNING available in DUT Control
Remote interface ports	IEEE-488, RS232C Serial, and Start Test/End of Test/Stop on First Fail (ST/ET/SFF) and Ethernet

Low Data Rate Environments (Thermo-Vac Testing)

- During Thermo-Vac, it can be difficult to connect external devices to the hardware subsystems (i.e. test equipment may not be used)
- On-board raw data mode and communications must collect and transfer data
- Raw data transfer for single range can take tens of milliseconds.
- Transfer of raw data to can take tens of minutes
- Excercising over various temperature and thermal conditions can take hours and even days.
- Measurement methodology assures that the "most efficient" method is used for critical end-to-end performance testing

Paper submitted for review regarding device characterization technique

IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, 2005

Two-Channel Phase, Amplitude and Timing Measurements for Radar Interferometry and Polarimetry

Paul Siqueira , *Member, IEEE* John Wirth and Alex Bachmann

Relationships between SNR and # of measurements related to measurement accuracy of phase, frequency, and amplitude

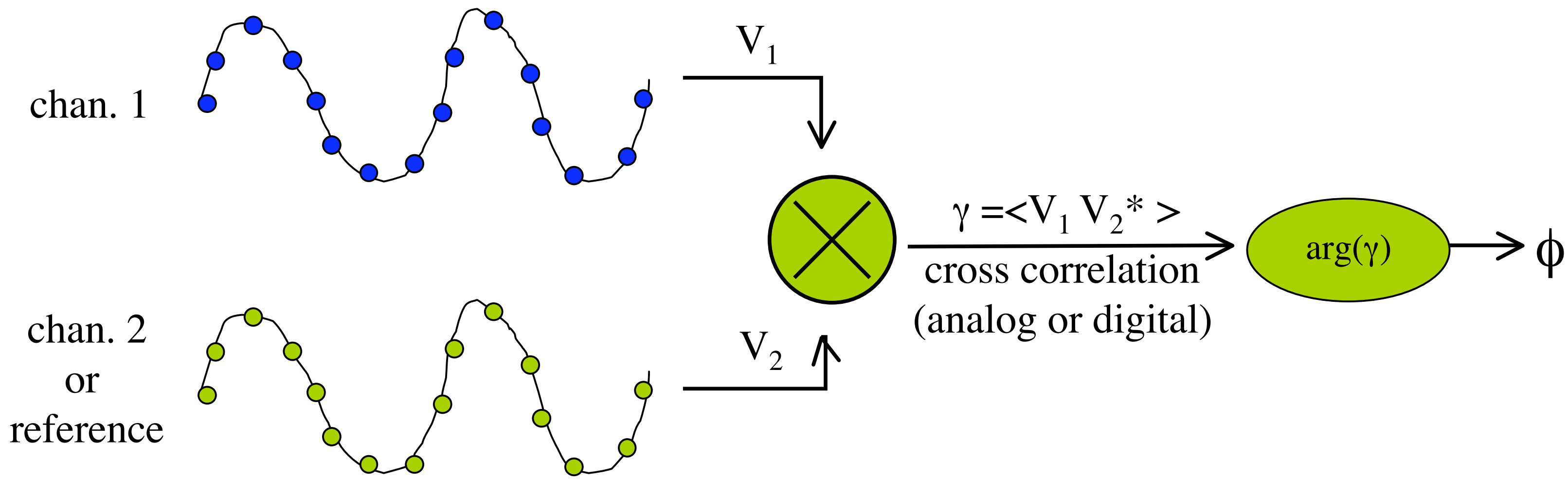
- important for determining accuracy and requirements for test equipment.

Conclusions

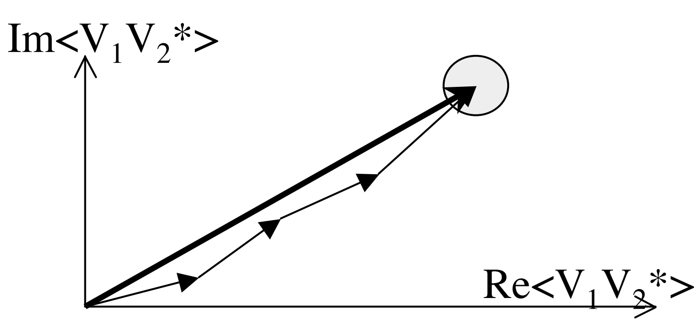
- Progress on design and measurements has been extremely good
- Student interest and involvement has been very high
- We are currently in the final design stages of the Ku-band downconverter
- Already doing preliminary tests for the Ka-band downconverter
- May construct a final version that will optimize w.r.t. weight & power, and qualify for flight

Supporting Slides

Measuring Phase

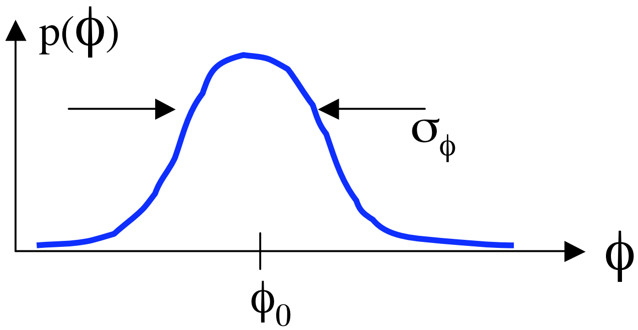


$$\sigma_\phi^2 \approx \frac{1}{2N}\frac{1-\gamma_{SNR}^2}{\gamma_{SNR}^2} \qquad \gamma_{SNR} = \frac{1}{1+1/SNR} \approx 0.9 \text{ when SNR} = 10\text{dB}$$

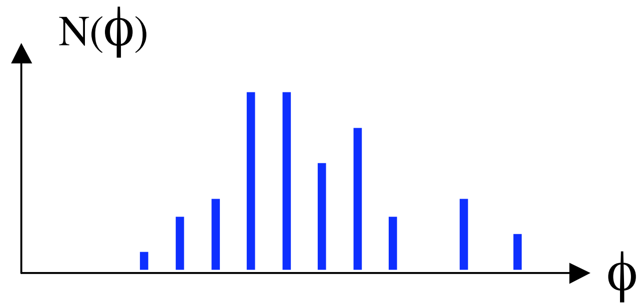


σ_ϕ	N	T (60MHz)
4 deg	24	400 nS
1 deg	400	6.7 µS
0.01 deg	3.9 Msamples	65 mS

Testing Phase Knowledge Requirements



Normal Distribution



Sample Distribution

Need to verify $\sigma_\phi < \sigma_{\phi limit}$

$$st.\,dev.(s^2) \approx \sqrt{\frac{2}{N}}\sigma^2 < \frac{\sigma^2}{M} \Rightarrow N > 2M^2$$

	M	*N*
$st.dev(s^2) < \frac{\sigma^2}{3}$	3	18
$st.dev(s^2) < \frac{\sigma^2}{10}$	10	200